Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 3548-3558

ECCOMAS Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

SCALING GROUND MOTION RECORDS BY CONSIDERING THE INELASTIC RESPONSE OF SOILS

Yeudy F. Vargas-Alzate [(1)], Ana M. Zapata-Franco [(2)], Rodolfo J. Tirado[(3)], Ramón González-Drigo[(4)], and Jean Vaunat[(5)]

[(1)] *Adjunct professor, Universitat Politècnica de Catalunya, yeudy.felipe.vargas@upc.edu*
[(2)] *PhD Student, Universitat Politècnica de Catalunya, ana.maria.zapata@upc.edu*
[(3)] *PhD Student, Universitat Politècnica de Catalunya, rodolfo.javier.tirado@upc.edu*
[(4)] *Full professor, Universitat Politècnica de Catalunya, jose.ramon.gonzalez@upc.edu*
[(5)] *Full professor, Universitat Politècnica de Catalunya, jean.vaunat@upc.edu*

Abstract

One of the main shortcomings of several seismic databases is the lack of ground motion records exhibiting high-intensity values. Consequently, when characterizing seismic risk, or in the design process of a civil infrastructure, it is generally necessary to scale up a significant amount of low-intensity records so that the nonlinear response of the analyzed system can be fully explored. However, this type of records does not reflect neither the stiffness degradation nor the increasing of damping in soils affected by high-intensity ground motions. This paper presents an innovative approach for scaling seismic records by taking into account both effects. To do so, the equivalent linear method has been employed in an iterative manner to scale up and get records meeting these important conditions. A database from Colombia containing almost two-thousand ground motion records has been used to characterize the seismic hazard. Results show that low-amplitude records scaled following the presented approach exhibit an increase of intensities at certain periods, which is consistent with the one observed in actual high-intensity ground motion records. In addition, the inelastic response of the soil tends to modify the expected risk, showing that scaling using constant values can produce biased results. It has been observed after comparing fragility functions derived for records scaled using a single scalar vs those considering the inelastic response of the soil.

Keywords: Scaling ground motion records, Stiffness degradation, Damping Increase, Equivalent linear method

ISSN:2623-3347 © 2023 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10659.21269

1 INTRODUCTION

In places of high seismic risk, and depending on the complexity (or importance) of a civil infrastructure, it is recommended to analyze its dynamic interaction with the ground through the use of advanced nonlinear models. There are several ways to model this interaction depending on the type of foundation [1]. Yet, in most cases, it is necessary to develop a set of signals that act at the base of a soil model, below which elastic rebound theory is expected to apply [2]. These signals should be recorded on a hard rock site for the last assumption to hold. Therefore, a key aspect of the study of seismic risk is the characterization of the dynamic response of the soil profile [3]. In this respect, it is common practice to use simplified 1D soil models to extensive 3D finite-element-method-based representations [4]. However, the higher the complexity of the model the higher the computational time involved in solving dynamic problems. In order to tackle this computational effort, more simplified soil models are widely used. One of the most employed is the 1D model, in which the soil layers are modeled as Kelvin–Voigt solids [5]. This model is represented by a purely viscous damper and purely elastic spring connected in parallel. In several cases, it allows a good approximation of the dynamic response of a soil mass. Moreover, this model has been extended to consider no-linearities associated to the loss of stiffness of the soil and the consequent increase in damping due to shear strains [6].

In line with the above, the frequency content of the ground motions at the surface produced by earthquakes depends on several complex phenomena like the type of rupture, the proximity to the epicenter and depth, and the mechanical properties of the media traversed by seismic waves. Regarding this latter, depending on the depth, seismic waves may degrade the stiffness of the media at very low shear strains [7]; the deeper, the less stiffness degradation. Therefore, in each location, there is a depth limit in which one could consider the stiffness degradation, and the consequent increase of damping, do not occur. Hence, close to the surface, and depending on the seismic intensity [8] and soil type, it is expected a significant degradation of the soil properties. This effect should be included when scaling the same ground motion record to several intensity values.

There are several methodologies to scale ground motions from a database. Typically, the goal is to find a significant set of records leading the structure to multiple performance levels. However, as indicated by the well-known Richter's law, the number of high-intensity ground motion records is much smaller than the number of low-intensity ones. Consequently, it is sometimes necessary to scale low intensity records by significantly high factors. In doing so, it has to be considered that some types of soil modify their dynamic properties at very low shear strains. Therefore, scaling a single record to increased intensity values may not take into account the likely inelastic response of soils. Accordingly, in this article is compared results stemming from two type of scaling methods: i) scale the entire ground motion record using a single scalar; ii) scale the record by considering the inelastic response of the ground, which implies an elongation of the fundamental period of the soil mass. To do so, a 5-storey reinforced concrete building has been used as a case of study. It has been assumed that this structure rests on a specific soil profile, which propagates seismic waves from the bedrock to the surface by considering the equivalent linear method. The resulting seismic waves at the surface are used to perform several nonlinear dynamic analyses of the structure. A database that collects almost two-thousand ground motion records acquired in Colombia has been used to characterize the seismic hazard. Finally, fragility functions based on both scaling approaches are derived and compared. This comparison indicates a non-negligible difference in the expected probabilities of damage.

2 MODELLING CONSIDERATIONS

2.1 Soil model

There are several ways to model the dynamic response of the soil beneath a structure [9]. The most appropriate way to do it depends to a large extent on the type of soil to be analyzed. In this article, the soil mass has been considered as a cohesionless soil, whose physical properties at very low shear strains are summarized in Table 1. This soil profile is thirty meters deep and it has been divided into eight different layers. Figure 1 shows the evolution with depth of the soil properties at very low shear strains.

Numerically, site response analysis based on 1D models can be performed using linear, equivalent linear and nonlinear methodologies. Amongst these three methodologies, equivalent linear is widely followed because of its simplicity and reasonable accuracy with respect to nonlinear-based results. This methodology has been used herein to assess the stiffness degradation and the consequent increasing of damping of the soil profile.

At present, there are numerous softwares and codes which can perform site response analysis following 1D models. In this article, the waveprop program has been used as solver to develop the iterative procedure related to the equivalent linear method [10].

Width (m)	Vs (m/s)	ρ (kg/m^3)	ξ
2.5	430	1947	0.037
3.5	515	1947	0.036
4.5	600	1947	0.035
3.0	655	2446.5	0.035
5.5	805	2446.5	0.034
4.5	1005	2446.5	0.033
3.0	1260	2446.5	0.033
3.5	1550	2446.5	0.032

Table 1 Soil properties at very low shear strains

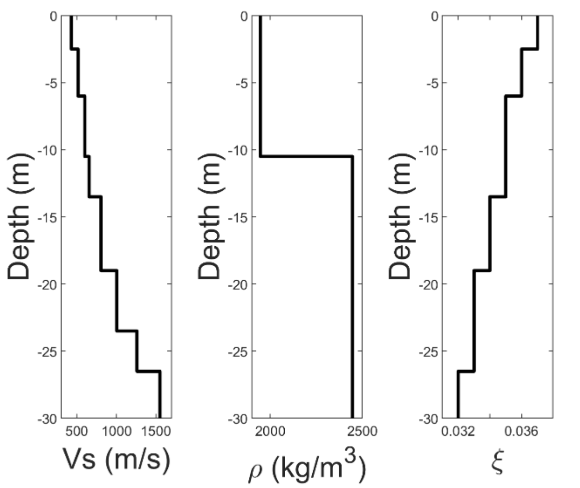

Figure 1 Scheme of the soil profile properties

2.2 Building model

As a case study, the five-story reinforced concrete building shown in Figure 2 has been analyzed. Table 2 summarizes the details of the main properties of its structural elements. This building rests on a soil profile whose dynamic properties at very low shear strains are the ones shown in Table 1. Thus, it has been assumed that seismic waves act at the top of the bedrock level (see Figure 2), from which elastic and inelastic propagations have been made towards the surface. Then, the resulting seismic waves have been used as input to perform structural calculations with the building model.

The modified Takeda hysteresis law, [11] has been used to represent the in-cycle behavior of the structural elements (beams and columns). This law allows considering strength degradation due to large deformations and excessive number of inelastic cycles. To do so, a strength degradation function, which depends on the ductility reached by the structural elements, as well as a degrading coefficient associated to the number of inelastic cycles has been considered in the hysteretic model [12]. For stiffness degradation, the degrading factor has been fixed to 0.4. The yielding surfaces are defined by the bending moment-axial load interaction diagram for columns and bending moment–curvature for beams. P-Delta effects has been considered in the numerical model, as the structure analyzed may experience deformations beyond the elastic range, sometimes exceeding their capacity to withstand gravity loads. The Ruaumoko software has been employed to perform the structural calculations [12].

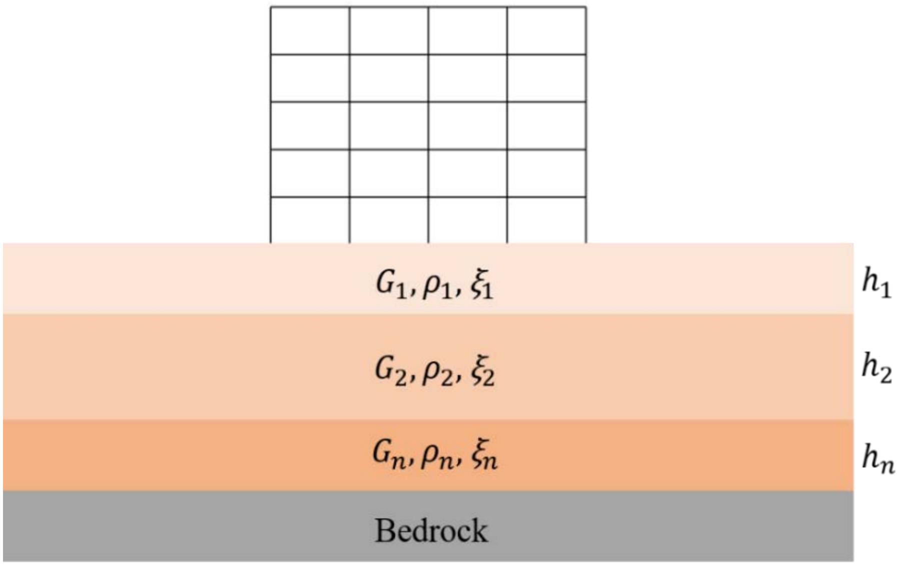

Figure 2 Soil and structural model

Story	W_c (m)	B_c (m)	W_b (m)	D_b (m)	ρ_c (%)	ρ_b (%)
1	0.55	0.55	0.30	0.40	1.5	0.66
2	0.55	0.55	0.30	0.40	1.5	0.66
3	0.50	0.50	0.30	0.40	1.5	0.66
4	0.50	0.50	0.30	0.40	1.5	0.66
5	0.45	0.45	0.30	0.40	1.5	0.66

Table 2 Characteristic of the structural elements. W_c and B_c represent the size of the columns; W_b and B_b represent the size of the beams; ρ_c and ρ_b represent the steel percentages of columns and beams, respectively

3 SEISMIC HAZARD

A compilation has been made of the ground motions recorded in Colombia between 1993 and 2017, with a magnitude greater than 4.0 Mw. These records have been extracted from the SGC [13]. They have been divided into two groups according to the ground conditions in which they were acquired. The first one corresponds to signals recorded on bedrock, from which a total of 1236 records were identified. The second group are signals recorded on less rigid ground, with a total of 756 records. Figure 3 shows the geometric mean of the horizontal spectra of these ground motion records. With the exception of a couple of ground motion records, this figure shows that the ground motions recorded in soils tend to provide increased spectral ordinates when compared to the ones acquired in rock. This can be easily seen by comparing some percentiles of both sets. Thus, Figure 4 compares percentiles 50th and 95th for records acquired in rock and soil. Two main conclusions can be drawn from this figure: i) Records acquired in soil provide higher spectral ordinates than the ones in rock; ii) the higher the intensity, the higher the response at higher period values. The latter can be seen in the 95th percentile figure, where two peaks appear in the soil spectrum. The one on the right side is likely to appear due to expected stiffness degradation for higher intensity values. It demonstrates the importance of accounting for this effect in the scaling process.

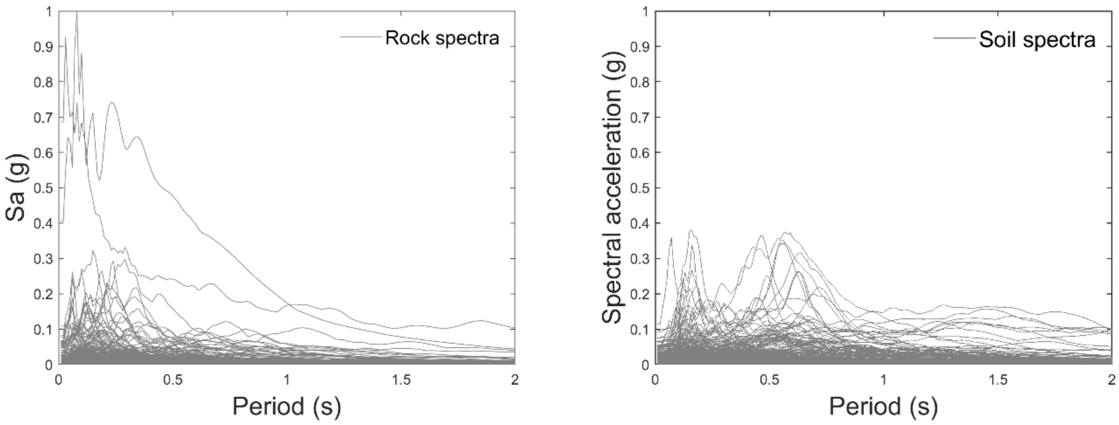

Figure 3 Geometric Mean Spectra of the horizontal components (Left: Rock Right: Soil)

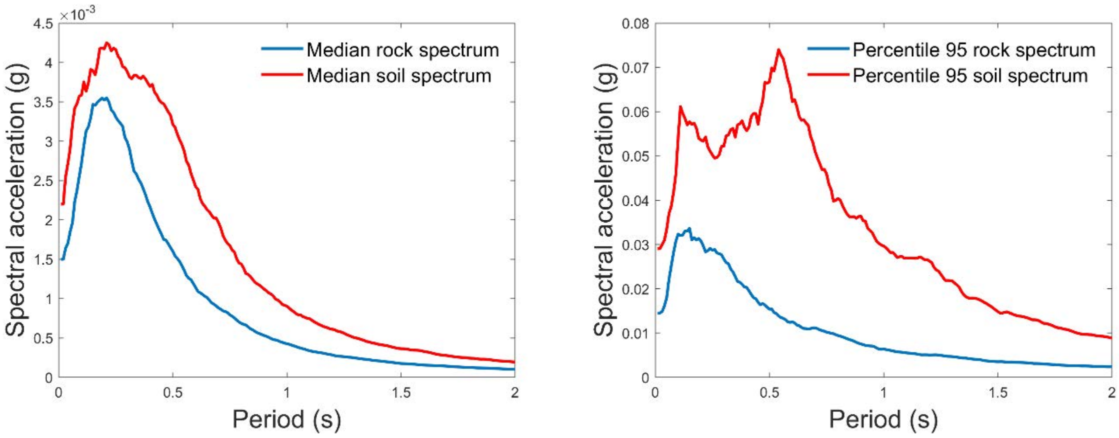

Figure 4 Median (Left) and percentile 95 (Right) of the entire set of spectra

From this database, one of the horizontal components of 20 ground motion records acquired in rock have been selected. These records have been used to analyze the influence of scaling, considering or not the effect of stiffness degradation.

4 EQUIVALENT LINEAR METHOD

The propagation of the seismic waves produces the degradation of the soil stiffness and, consequently, the increase of the material damping in each layer. These changes depend on the maximum shear strain reached during a seismic event. There are several methods to consider this modification of the physical properties of the soil in the seismic analysis. One of the most used is the linear equivalent method. This method consists in estimating, from iterative linear approximations, the physical properties of a modified soil profile, whose elastic dynamic response is similar to that obtained via nonlinear dynamic analysis. These calculations are performed in the frequency domain, which substantially reduces the computational effort.

In the equivalent linear method, the degradation of the stiffness, and the consequent increase in the damping of the material in each layer, are considered using the normalized shear modulus (G/Gmax) and hysteretic damping curves; both as a function of the maximum shear strain reached during the dynamic process. For the case of study, these reference curves have been selected from the EPRI report for a cohesionless soil [14]. Figure 5 shows the stiffness degradation and damping curves used in this study.

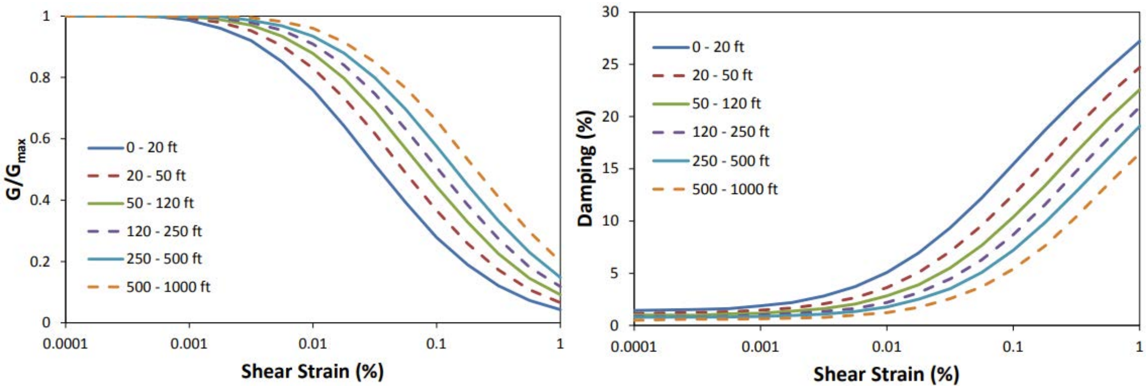

Figure 5 G/Gmax and hysteretic damping as a function of the shear strain for a cohesionless soil, [14]

In the following, the iterative process associated with the equivalent linear approximation is described step by step:

1. Initially, each soil layer is modeled considering values of stiffness (G_0) and damping (ζ_0) corresponding to very low shear strains (<10-3) (see Table 1)
2. From the properties described in the previous step, the history of shear strains in each soil layer is calculated, $\gamma(t)$
3. From the maximum strain reached during the propagation, $\gamma_{max} = \max(|\gamma(t)|)$, the effective strain in each layer is estimated as $\gamma_{eff} = \alpha * \gamma_{max}$; in this research α =0.65
4. For each layer, a new pair of G_i and ζ_i values is obtained from the degrading curves for stiffness and damping (see Figure 5)
5. Steps 2 to 4 are repeated until the difference between two consecutive values of G_i and ζ_i are less than 1%
6. From the final values of G and ζ, for each soil layer, a linear site response analysis can be performed

This procedure has been used to estimate the nonlinear response of the soil profile shown in Figure 1 in front of a set of linear scaled versions of the 20 ground motion records selected from the Colombian database. That is, each ground motion record has been scaled so that an intensity measured identified as AvSv [15] ranges from 0.02 m/s, at intervals of 0.02 m/s, until reaching a value equal to 1 m/s. Figure 6 shows the resulting spectra of the ground motion at the surface after applying the equivalent linear method. The spectra of records whose AvSv value is equal to 0.2 m/s have been included in order to show the elongation of the fundamental period of the soil profile for higher intensity values. It can be seen that depending on the ground motion record, the stiffness degradation is variable. Anyhow, the increased response at elongated periods observed in Figure 6 is consistent with that of the real records (see Figure 4, left).

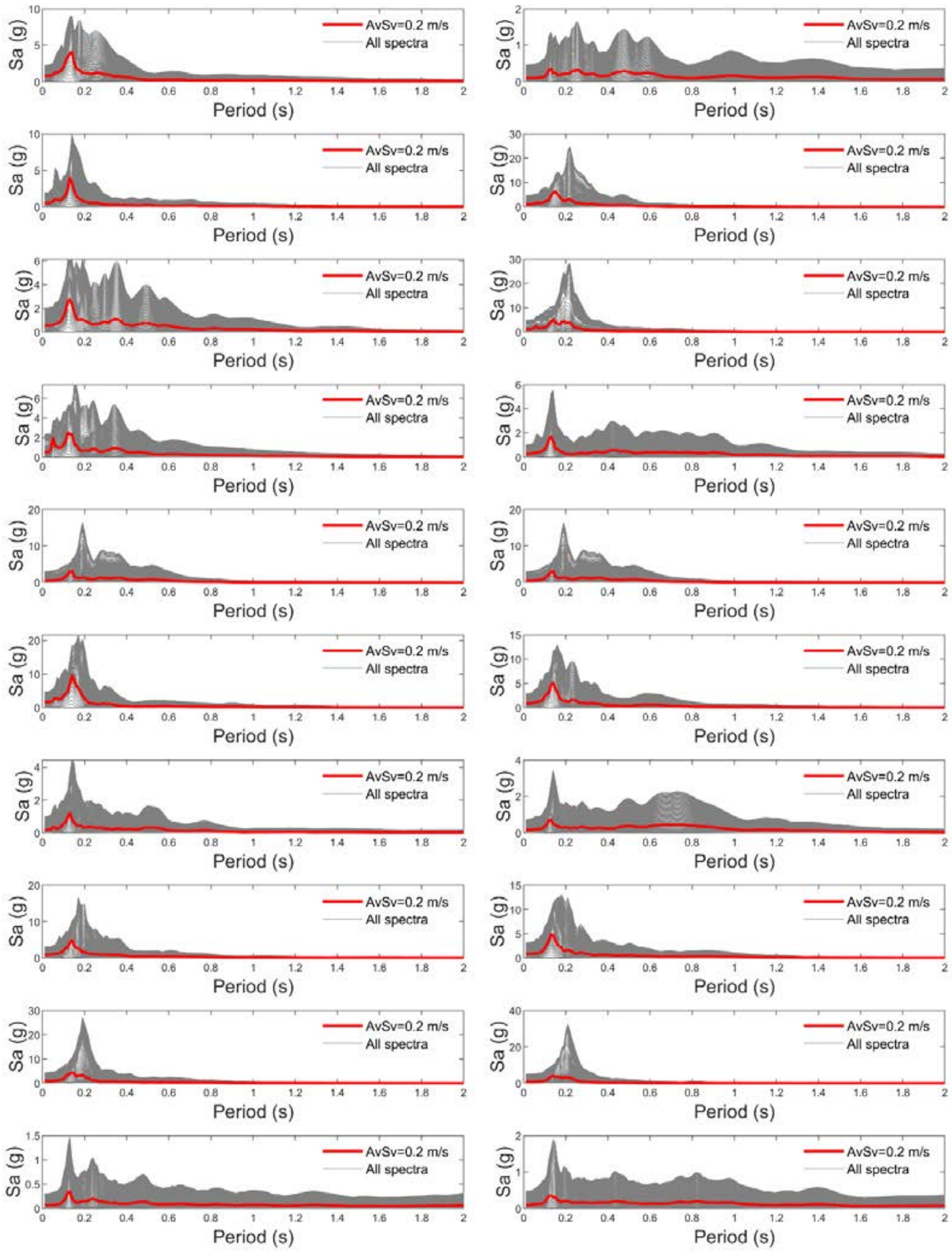

Figure 6 Spectra of the scaled records by considering the equivalent linear method

As discussed above, two approaches are considered when seismic waves traverse the soil profile (elastic and inelastic). Therefore, the set of seed signals has also been scaled using a linear propagation method. Figure 7 shows the resulting spectra at the surface after this operation. Again, the spectra of the records scaled so that AvSv equals 0.2 m/s have been highlighted in red as reference.

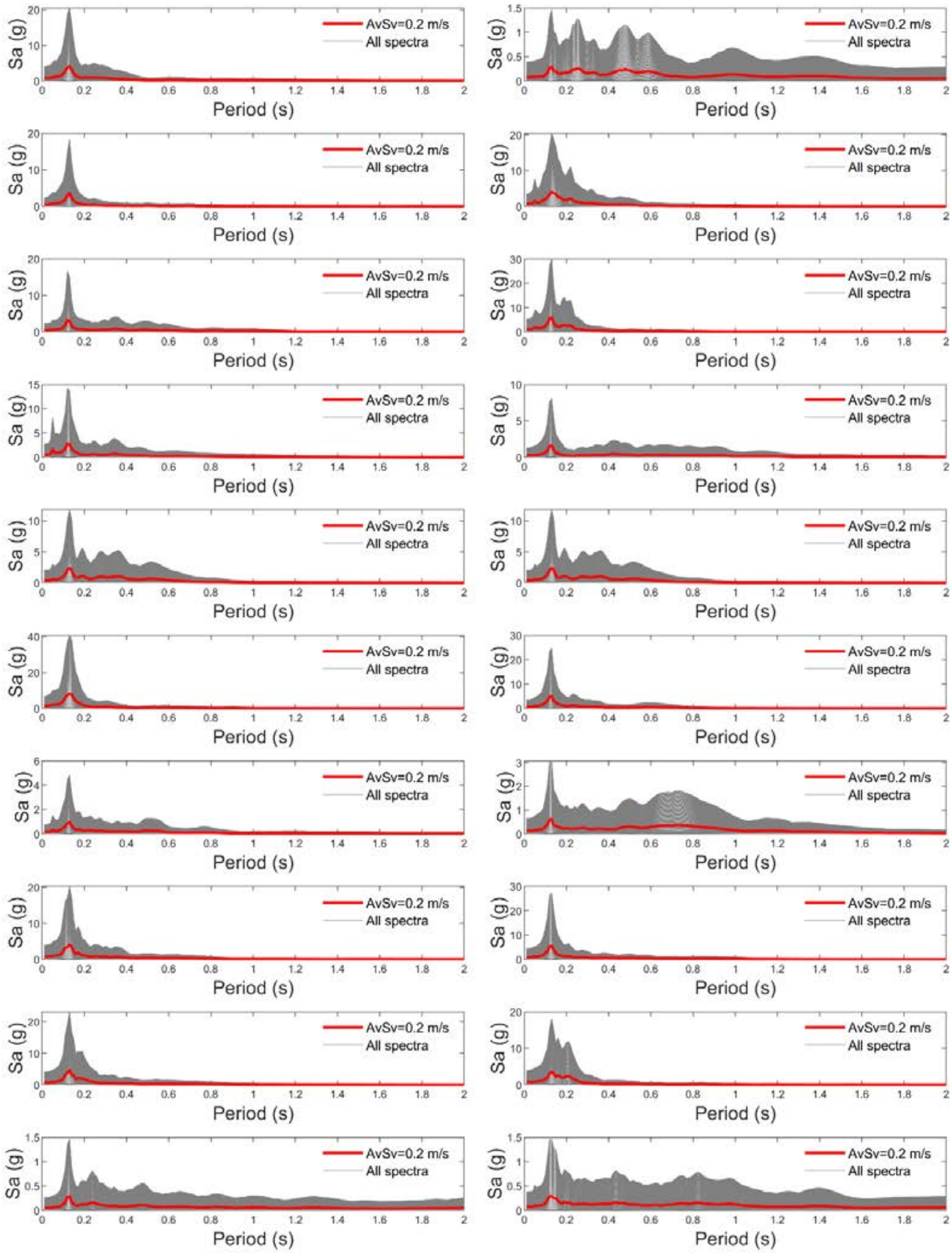

Figure 7 Spectra of the scaled records by considering a linear method

The resulting ground motions at the surface derived from both scaling approaches are then used as input to the building model. The nonlinear dynamic analysis has been used to perform these calculations. From each analysis, the maximum inter-storey drift ratio (MIDR) has been calculated and considered as engineering demand parameter (EDP).

5 FRAGILITY ANALYSIS

From the AvSv-MIDR relationship, one could derive fragility functions according to the so-called 'cloud analysis' approach [16]. This methodology requires to calculate the best fit curve between a set of IM and EDP realizations in the log-log space. In general, the aforementioned fitting is performed using linear regression analysis. However, some IM-EDP clouds are better represented by considering a nonlinear regression analysis [15]. This type of regression has been employed in this research. Then, the resultant curve is used to estimate the median of a parametric statistical distribution, given an IM value. The variability of this parametric distribution is estimated as the standard deviation of the IM-EDP residuals with respect to the fitted curve. In this way, the probability of exceeding a certain damage threshold can be calculated. These thresholds are particular realizations of the EDP under consideration, EDP_C.

Figure **8** shows the AvSv-MIDR pairs obtained based on both scaling approaches. It can be seen that at lower intensity values, MIDRs coming from the linear propagation method tend to be higher than those based on the equivalent linear method. At higher intensity values, this tendency is not that clear.

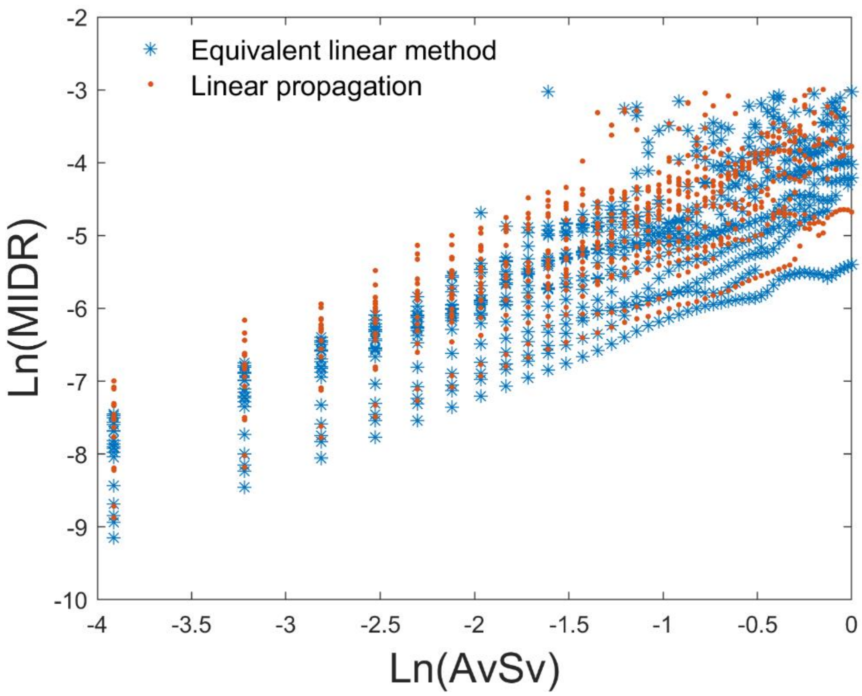

Figure 8 Clouds of IM-EDP points for both scaling approaches

Then, fragility curves for two performance levels have been derived: *slight* and *extensive*. They can be related to MIDR values equal to 0.005 and 0.02, respectively. Hence, Figure 9 shows the fragility functions for both damage thresholds and by considering both scaling approaches. In this figure it is also shown the absolute value of the difference in probability between both scaling methods. These functions show that the difference in probability can reach values of the order of 0.2 for the slight damage state whilst for the extensive 0.1. In both cases, a significant shift between fragility curves related to the same damage state can be observed.

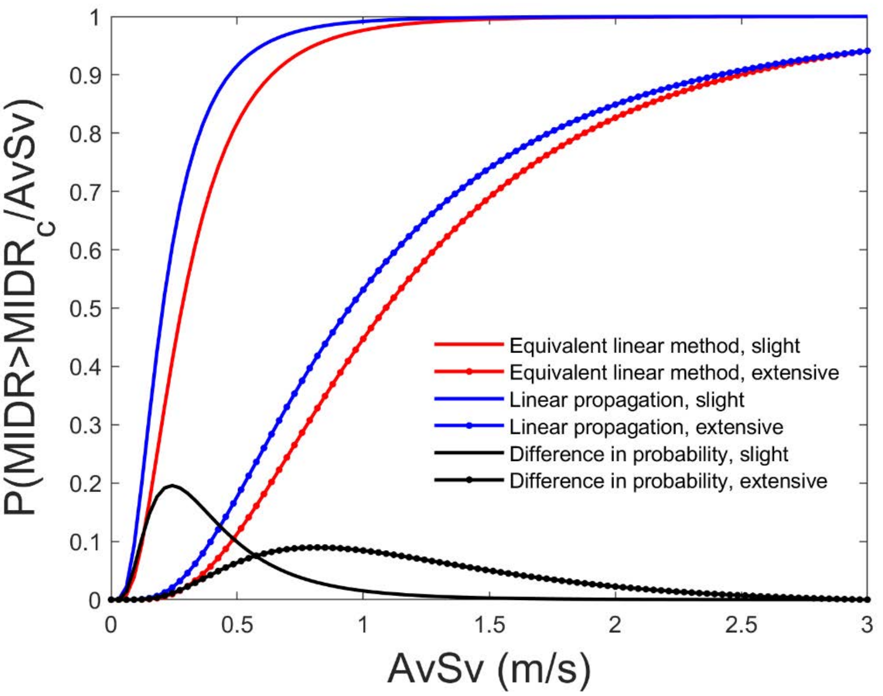

Figure 9 Fragility curves considering both scaling approaches

6 CONCLUSIONS

In this article, it has been analyzed the influence on the derivation of fragility functions when scaling ground motion records by taking into account the modification of the dynamic properties of the soil mass below a structure. As a case of study, a soil profile of cohesionless material and a 5-storey reinforced concrete building have been analyzed. Seismic hazard has been characterized by using a set of ground motion records acquired in Colombia [13]. These seed records have been scaled considering or not the influence of the stiffness degradation in the soils due to seismic waves. Using these records, several nonlinear dynamic analyses have been performed. Finally, fragility functions have been derived and compared.

The main conclusion of this study is that the consideration or not of the stiffness degradation of soils, when scaling, affects the derivation of fragility curves. However, the results are far from conclusive that the fragility functions derived by considering soil stiffness degradation always provide lower exceedance probabilities than those associated with linear propagation. This is because only one soil profile and one building model have been analyzed.

Advanced probabilistic calculations that consider the highly probabilistic nature of both the dynamic properties of soil and buildings can shed light on this regard. This would allow the development of advanced mathematical arrangements that take into account the influence of the main properties of the ground motion record applied at the bedrock level and the dynamic properties of soil and buildings.

ACKNOWLEDGMENT AND FUNDING

This research has been funded by the Spanish Research Agency (AEI) of the Spanish Ministry of Science and Innovation (MICIN) through the projects with references: PID2020-117374RB-I00/AEI/10.13039/501100011033 and TED2021-132559B-I00 – J-02970.

REFERENCES

[1] Lou, M., Wang, H., Chen, X., & Zhai, Y. (2011). Structure–soil–structure interaction: Literature review. Soil dynamics and earthquake engineering, 31(12), 1724-1731.

[2] Ohnaka, M. (1976). A physical basis for earthquakes based on the elastic rebound model. Bulletin of the Seismological Society of America, 66(2), 433-451.

[3] Pagliaroli, A., Lanzo, G., Tommasi, P., & Di Fiore, V. (2014). Dynamic characterization of soils and soft rocks of the Central Archeological Area of Rome. Bulletin of earthquake engineering, 12(3), 1365-1381.

[4] Kaklamanos, J., Baise, L. G., Thompson, E. M., & Dorfmann, L. (2015). Comparison of 1D linear, equivalent-linear, and nonlinear site response models at six KiK-net validation sites. Soil Dynamics and Earthquake Engineering, 69, 207-219.

[5] Hardin, B. O., & Scott, G. D. (1966). Generalized Kelvin-Voigt used in soil dynamics study. Journal of the Engineering Mechanics Division, 92(1), 143-156.

[6] Yoshida, N., Kobayashi, S., Suetomi, I., & Miura, K. (2002). Equivalent linear method considering frequency dependent characteristics of stiffness and damping. Soil Dynamics and Earthquake Engineering, 22(3), 205-222.

[7] Okur, D. V., & Ansal, A. (2007). Stiffness degradation of natural fine grained soils during cyclic loading. Soil Dynamics and Earthquake Engineering, 27(9), 843-854.

[8] Kostinakis, K., Fontara, I. K., & Athanatopoulou, A. M. (2018). Scalar structure-specific ground motion intensity measures for assessing the seismic performance of structures: a review. Journal of Earthquake Engineering, 22(4), 630-665.

[9] Wong, H. L. (1975). Dynamic soil-structure interaction.

[10] Dimitris Pitilakis (2023). waveprop, MATLAB Central File Exchange.

[11] Otani S (1974) Inelastic analysis of RC frame structures. J Struct Div ASCE 100:1433–1449

[12] Carr AJ (2000) Ruaumoko-inelastic dynamic analysis program. University of Canterbury, Department of Civil Engineering, Christchurch

[13] Colombian geological survey (SGC), Sistema de Consulta de la Amenaza Sísmica de Colombia. https://amenazasismica.sgc.gov.co/ (accessed January, 2023).

[14] ELECTRIC POWER RESEARCH INSTITUTE, «Seismic Evaluation Guidance - Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic» Report 1025287, Palo Alto, CA, February 2013.

[15] Vargas-Alzate, Y. F., Hurtado, J. E., & Pujades, L. G. (2022). New insights into the relationship between seismic intensity measures and nonlinear structural response. Bulletin of Earthquake Engineering, 1-37.

[16] Jalayer F, De Risi R, Manfredi G (2015) Bayesian cloud analysis: efcient structural fragility assessment using linear regression. Bull Earthq Eng 13:1183–1203