UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

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Homogenization of a Random Field in the Propagation of Seismic Waves

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Ingeniería Civil

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Homogenization of a Random Field in the Propagation of Seismic Waves

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RESUMEN

La variabilidad inherente de los suelos está influenciada por la historia geológica del depósito, así como por procesos como la infiltración, la diagénesis y la meteorización física, química o biológica. En este estudio, MATLAB y OpenSees se utilizaron para crear un modelo computacional que genera un campo aleatorio y luego lo homogeneiza. Por tanto, la investigación compara la respuesta dinámica en superficie de un depósito de suelo homogéneo con uno heterogéneo utilizando la aceleración espectral. La simulación se ha realizado para sismos con frecuencias predominantes de 2,5 Hz y 12 Hz, considerando suelos arcillosos finos con un rango del límite líquido de 87% a 348%, y para una longitud de correlación de 4 m. Los resultados muestran que un campo aleatorio se puede homogeneizar utilizando el modelo computacional, obteniendo resultados precisos con un error del 30 % para el límite superior y del 40 % para el límite corregido. Las limitaciones del modelo homogéneo, sin embargo, se encontraron para periodos de vibración de 0.7s a 1.7s, donde se obtuvieron errores máximos. Para mejorar la precisión y aplicabilidad del modelo, se requiere más investigación, donde se debería analizar los efectos de varios parámetros, como la variabilidad del suelo, el análisis de cortes verticales adicionales y el modelado de más ondas sísmicas. La metodología de la investigación se puede utilizar para evaluar los riesgos sísmicos y diseñar edificios que puedan resistir terremotos, especialmente en países propensos a los estos como Ecuador. Además, debido a que las pruebas dinámicas para determinar la velocidad de la onda de corte en un depósito son costosas, la homogeneización de un depósito resultar en ahorros financieros significativos.

Palabras clave: Campos aleatorios, homogeneización, módulo de corte máximo, aceleración espectral, análisis dinámico, propagación de ondas sísmicas.

ABSTRACT

The inherent variability of soils is influenced by the geological history of the deposit as well as processes like infiltration, diagenesis, and physical, chemical, or biological weathering. In this study, MATLAB and OpenSees are used to create a computational model that generates a random field, and then homogenizes it. Therefore, the research compares the dynamic response on surface of a homogeneous soil deposit with a heterogeneous one using the spectral acceleration. The simulation has been done for earthquakes with predominant frequencies of 2.5 Hz and 12 Hz, considering fine clayey soils with a liquid limit range from 87% to 348%, and for a correlation length of 4 m. The outcomes show that a random field can be homogenized using the computational model, obtaining accurate results with 30% error for the upper limit and 40% for the corrected limit. The homogeneous model's limitations, however, were found for vibration periods from 0.7s to 1.7s, where maximum errors where obtained. To improve the model's accuracy, more research is required. This future research should look at the effects of various parameters, such as soil variability, additional vertical cuts analysis, and modeling more seismic waves to broaden the model's applicability. The research's methodology can be used, especially in countries like Ecuador that are prone to earthquakes, to evaluate seismic risks and design earthquake-resistant buildings. Accurate homogenization in determining the dynamic seismic response of a soil deposit can also result in significant financial savings, due to expensive dynamic tests required to determine the shear wave velocity in a deposit.

Key words: Random fields, homogenization, maximum shear modulus, spectral acceleration, dynamic analysis, seismic wave propagation.

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1. INTRODUCTION

Engineers face significant difficulties when analyzing the propagation of seismic waves due to the heterogeneity of soil deposits. Since geological and environmental processes shape and continuously alter soils, resulting in variability in the spatial distribution of their mechanical properties, soils are highly variable materials (Pua L., et al, 2021). The distribution of soil's complex and variable physical and mechanical properties can have a big impact on how well waves travel through them. Because of this variability, it is difficult to predict with accuracy how soil deposits will react to seismic events. The performance of structures built is highly impacted by the spatial variability of the properties of the soil underneath.

Spatial variability is the term used to describe variations in soil properties that can differ in each geometric direction. In geotechnical engineering, random fields are frequently used to describe the spatial distribution of soil properties. This method has grown in popularity because it can simulate them in a deposit with controlled variables, even when the deposit’s stratification is not completely known. Soil characteristics are regarded as stochastic variables in a random field and are described by their mean values, probability distribution functions, and correlation length (Baker, 1984). The geological history of the deposit as well as procedures like infiltration, diagenesis, and physical, chemical, or biological weathering all affect the inherent variability of soils.

To simulate the spatial variability of soil properties like density, velocity, or its Atterberg Limits (as it is done in this research), random fields are very useful. Spatial correlation lengths, which show how soil properties are correlated at various distances, are typically used to represent random fields. When a system is homogenized, its complexity is decreased by treating it like a homogeneous medium with uniform properties.

Homogenization is used in the context of seismic wave propagation to make it easier to analyze the seismic response of a soil with random properties. When a wave travels through an elastic medium, such as rock or soil, it engages in a complicated process known as seismic wave propagation. The characteristics of the medium and the source of the movement affect how seismic waves travel. This analysis gets complex when inelastic properties are considered. The degradation curve G/Gmax illustrates how the shear modulus (G) decreases relative to the maximum shear modulus (Gmax) as the deformation applied to the surface increases. This curve provides information on how the soil's rigidity behaves as it is subjected to greater degrees of deformation, information that may be helpful in the analysis of the seismic response. Experimentally, the expression for the degradation curve for each node was taken from a stiffness investigation of soils (Vardanega & Bolton, 2013).

In the following research, the properties of the soil deposit were modelled as a random field, by spatially distributing the Liquid Limit. The random field can then be homogenized to create a medium that is equivalent and still maintains the fundamental characteristics of the original field. It has the potential to be a useful tool in civil engineering to assess the seismic hazard in soil deposits because homogenization has demonstrated promising results in predicting the seismic response of soil deposits. Using the bounding limits suggested by (Hashin & Shtrikman, 1963) for composite materials, the maximum shear modulus was calculated for what it be called as upper limit, lower limit, and corrected limit. Elastic constants, like saturated specific weight and shear modulus, of the individual components of a composite material are used to evaluate the bounds along with the stored strain energy. Therefore, this study examines the homogenization of a random field during seismic wave propagation in a soil deposit, with a focus on the use of this method to examine the dynamic responses of a soil column in the surface. The findings of this study will advance knowledge of how soil deposits behave under seismic loads.

This work consists primarily of two parts. The first one is the generation of a MATLAB routine, capable of creating a random field with the spatial distribution of the Liquid Limit for clayey soils. This was based on data taken from laboratory essays made of eight sample mixes, with different content of kaolin and bentonite percentages (Pua L., et al, 2021). Then, the deposit will be normally consolidated, considering a water position at 5 m below the surface, obtaining the void ratio for each point of the deposit. With the void ratio and the Atterberg property randomly distributed according to a specific correlation length, geotechnical properties were derived like the specific saturated weight, the shear wave velocity, and the shear modulus. Once all these properties are generated, the second part of the research consists of a one-dimensional wave propagation model, considering vertical soil columns in the deposit and analyzing the dynamic response in the surface. Two seismic accelerations selected as base inputs are introduced in the finite element model created in OpenSees. The dynamic response will be evaluated for the heterogeneous model, as well as for the homogeneous models (Upper Limit, the Lower Limit, and the Corrected Limit). Finally, there will be included an analysis of the most accurate homogeneous model.

2. TOPIC DEVELOPMENT

2.1. Materials and methods

Materials and methods are discussed in the following sub-sections. The materials segment characterizes soils' properties used in this investigation. The methodology is divided into two stages. The first one consists in the generation of the soils' deposit using the random field theory. The second stage consists in the seismic response analysis of heterogenous and homogeneous soils samples, using a one-dimensional wave propagation model.

2.1.1. Materials

This investigation evaluates a soil deposit based on eight fine clayey soils samples, artificially made up with different percentages of kaolin and bentonite content, from a study made in Colombia (Pua L., et al, 2021). Each sample was normally consolidated with stresses from 4 kPa to 50 kPa. Table 1 shows every sample's proportion, its Atterberg limits (Liquid Limit, Plastic Limit and Plastic Index), the void ratio at 50 kPa, the compression index and the maximum shear modulus at 50 kPa.

Table 1. Properties of each soil sample (Pua L., et al, 2021).

Soil	Kaolin	Bentonite	Colorant	Atterberg limits			e_{50kPa}	C_c	$G_{max\text{-}50kPa}$
				W_L	W_P	PI			
	(%)	(%)	(%)	(%)	(%)		(–)	(–)	(MPa)
S1	100	0	0	87	44	43	2.05	0.56	5.80
S2	68	23	9[a]	120	25	95	2.28	1.35	2.79
S3	55	33	12[b]	148	22	126	2.76	1.91	2.57
S4	44	44	12[c]	196	19	177	2.93	2.08	3.02
S5	31	52	17[d]	204	20	184	2.87	2.10	2.82
S6	21	63	16[e]	234	22	212	3.60	3.27	1.77
S7	10	73	17[f]	300	29	271	3.97	3.80	2.14
S8	0	100	0	348	30	318	4.39	5.65	1.24

**Colorant proportions: a. 9%: 2% red and 7% yellow, b. 12%: 8% red and 4% yellow, c. 12%: 8% yellow and 4% black, d. 17% red, e. 16% yellow, f. 17% black.

It was shown that samples cover a liquid limit range from 87%-348%. Additionally, the void ratio goes from a value of 2.05 for the first sample, to 4.39 for the eighth sample. These values show the initial conditions under which this investigation works. For granular soil deposits, as well as for higher or lower liquid limits values than the range shown above, this current investigation does not apply.

An exponential regression for the data shown was made. The maximum shear modulus (G_{max}) measured for each sample was determined by an interpolation process, where the equation shown in figure 1 was applied, with some changes.

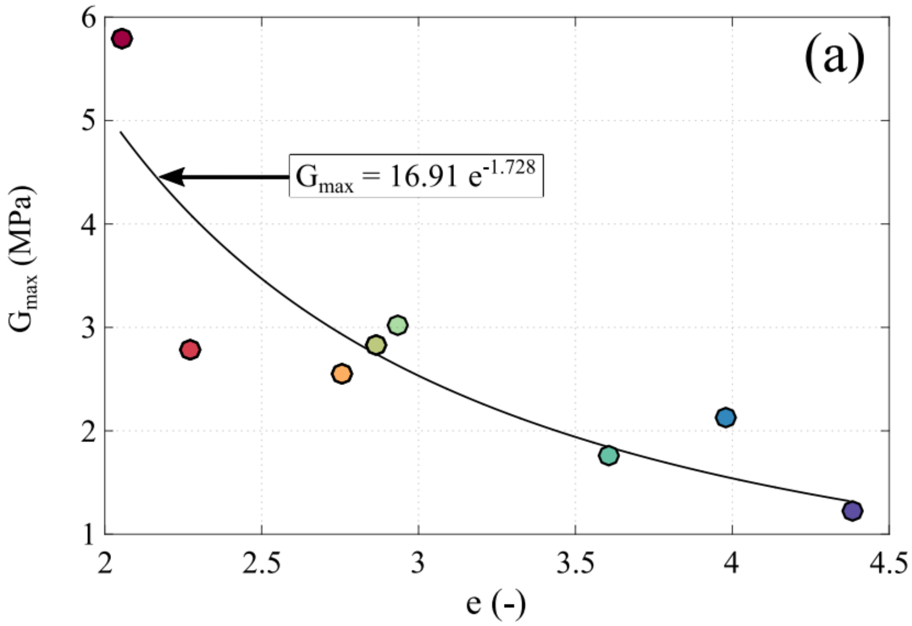

Figure 1. Regression for void ratio and max shear modulus for a constant stress of 50 kPa (Pua L., et al, 2021).

Since the equation showed on figure 1 was performed for a constant vertical stress of 50 kPa, the equation was normalized so it can be applied for larger vertical stresses using the equation 1:

$$G_{max} = 16.91\, e^{-1.728} * \left(\frac{\sigma_0}{50}\right)^{0.5} \tag{1}$$

Where σ_0 is the effective vertical stress, and it can be determined using the equation 2 (Das B., 2011):

$$\sigma_0 = \frac{1}{3}(\sigma_v + 2 * k_0 \sigma_v) \tag{2}$$

And for normally consolidated clays, k_0 is the at-rest earth pressure coefficient, and according to Das B. it can be calculated using equations 3 and 4 (2011):

$$k_0 = 0.4 + 0.007\, IP \quad (for\ 0 \leq IP \leq 40\%) \qquad (3)$$

And

$$k_0 = 0.68 + 0.001(IP - 40) \quad (for\ 40\% \leq IP \leq 80\%) \qquad (4)$$

2.1.2. Methods

2.1.2.1. Random Field Generation

Stochastic models known as random fields are used to describe how a quantity of interest (Liquid Limit in this case) changes over a specific area of space or time. Random fields are a tool used in geotechnical engineering to model the spatial variability of soil properties like soil stiffness, damping, strength, and properties such as Atterberg Limits. The spatial variability of soil properties has an impact on the dynamic response of structures built on soil deposits. As a result, the inclusion of random field models is necessary for the analysis of the dynamic response of structures, when a deposit has not been classified.

To make the mathematical characterization of the random field simpler, three assumptions were made: that the process is Gaussian, stationary, and isotropic (Pua L., et al, 2021). Therefore, the random field for the Liquid Limit mainly depends on the mean (μ), the coefficient of variation (COV) and the correlation length (θ). Based on the data obtained from Pua's investigation, there was taken a mean value of 210% (Pua L., et al, 2021). For the COV, a recommended value of 25% was taken (Muñoz and Caicedo, n.d.). Finally, the correlation function, which describes the statistical dependence between the values of the quantity of interest at various locations in the field, is what distinguishes random fields. The random field is realized using the correlation function, and these realizations can be used to run simulations or statistical analyses. Using small correlation lengths will lead to a greater spatial variability of the deposit, meanwhile larger values will decrease variability, and lead to a more homogeneous deposit. As an initial value, it was taken a correlation length of 4.00 m.

This investigation uses the matrix decomposition method to generate the random field (El-Kadi and Williams, 2000). Additionally, Baker used a finite difference approach to solve some differential equations to model a random field, based on soils' variability (1984). The generated random field is a bidimensional model of a tridimensional deposit, as it shows an elevation cut. Figure 2 shows the spatial distribution of the Liquid Limit generated by a routine in MATLAB, where the vertical axis (z) represents the deposit depth (30 m), and the horizontal axis (x) represents its length (50 m). As it is shown, the random field has a maximum value of 382%, and a minimum value of 77%.

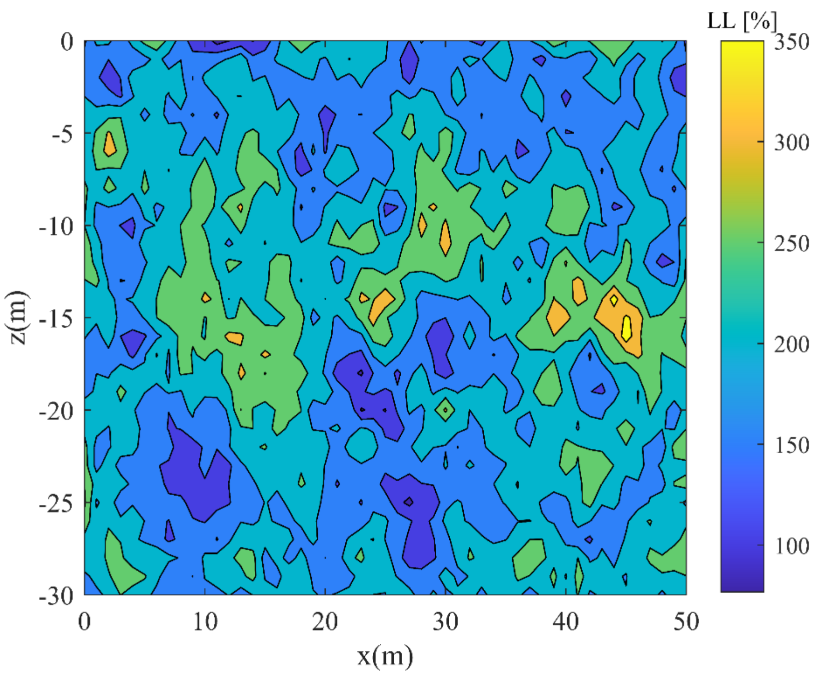

Figure 2. Liquid Limit spatial distribution.

Moreover, the deposit was normally consolidated, considering a water position of 5 m from the surface of the deposit. Based on the effective stress that relies on each node, and considering the consolidation data from table 1, the void ratio was calculated by interpolating the liquid limit of each of the consolidation curves obtained for the eight soil samples data. Figure 3 shows the spatial distribution of the void ratio generated by a routine in MATLAB. It was obtained a minimum value of 1.53 at the bottom of the deposit, meanwhile a maximum value of 3.96 was registered at the surface. Smaller values of the void ratio are shown at the bottom, due to a greater stress received, which compact the soil.

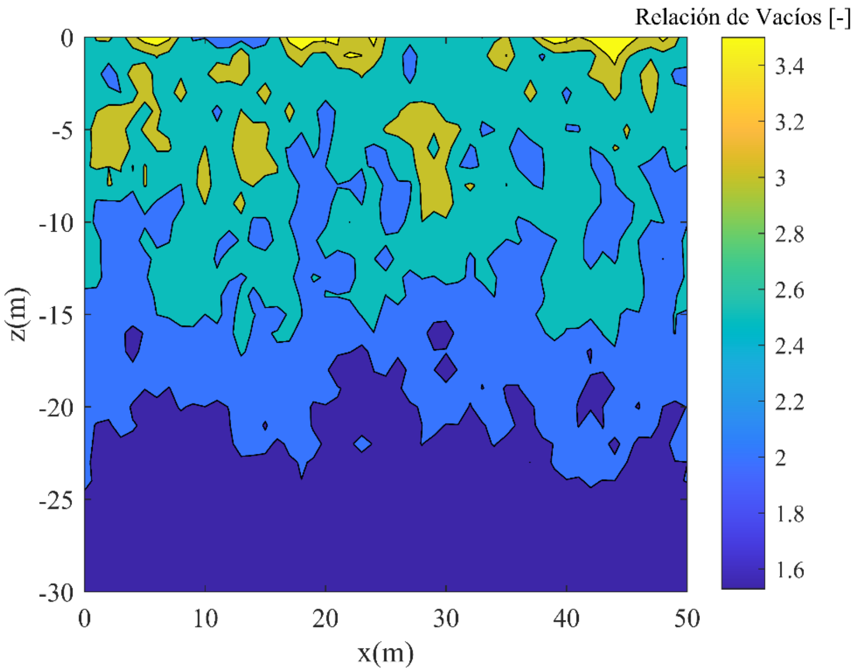

Figure 3. Void ratio spatial distribution.

With the void ratio distribution of figure 3, and with the equation number 1, it was possible to determine the maximum shear modulus with its spatial distribution in the whole deposit. The shear modulus represents the maximum stiffness that a soil can exhibit under shear deformations. Figure 4 shows the spatial distribution of the maximum shear modulus. The modulus increases with the deposit depth, as it was expected. It has a maximum value of

14.09 MPa at the bottom and a minimum value of 1.52 MPa at the surface. Large shear modulus values indicates that the soil sample is much stiffer.

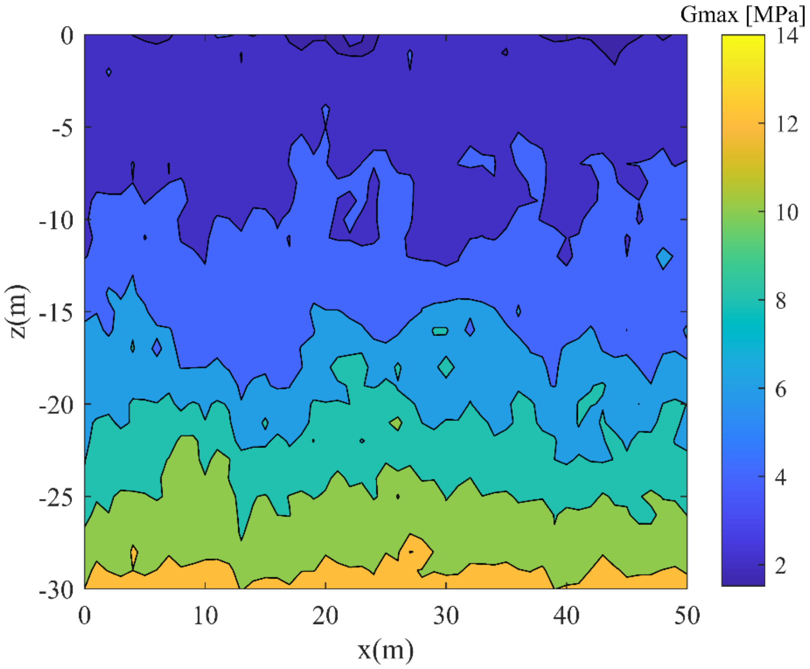

Figure 4. Maximum shear modulus spatial distribution.

The distributed saturated specific weight of the entire deposit is one of the geotechnical parameters obtained through the investigation. Figure 5 shows the spatial distribution of the saturated specific weight. Lower densities are found in the upper part, and it is evident that this value rises as depth increases. This demonstrates that the clayey soil is looser in the first few meters and gradually becomes denser because of the geostatic stress. A maximum value of 16.13 kPa is obtained near the bottom, meanwhile a minimum value of 13.12 kPa is obtained near the surface.

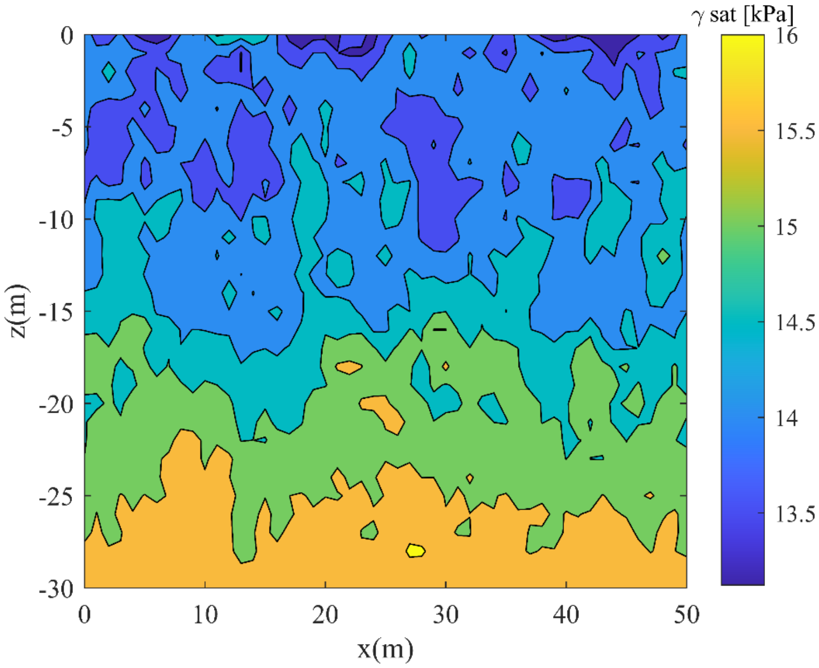

Figure 5. Saturated specific weight spatial distribution.

Additionally, figure 6 shows the shear wave velocity spatial distribution. The velocity range of the randomly generated deposit is 33.69 m/s to 92.56 m/s. The stiffness of the soil in each layer can be estimated from the shear wave velocity. Surface velocities are low, but as the deposit descends, they rise. Soft soils are characterized by low shear wave velocities, whereas stiffer soils are characterized by high velocities. This decrease in surface shear wave velocity corresponds to a change in the surface frequency content. In other words, soft soils may lead to a seismic amplification or de-amplification.

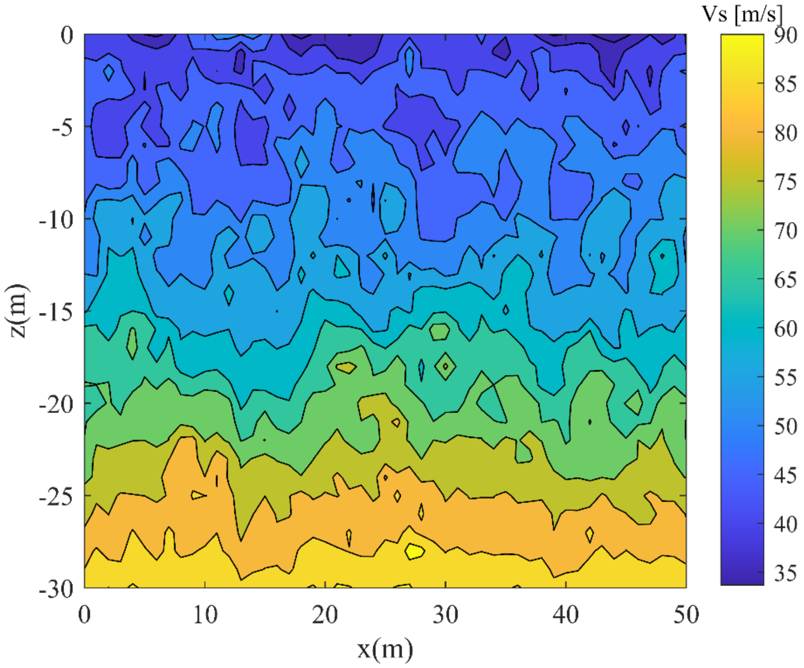

Figure 6. Shear wave velocity spatial distribution.

Finally, the model proposed considers the non-elastic behavior of the material. The decrease in soil resistance caused by the application of an increasing number of load cycles is represented by soil degradation curves. These curves are obtained through cyclic load tests, which involve repeatedly applying a load to a soil sample and measuring the amount of deformation that results from each cycle. The degradation curve shows the correlation between the deformation's amplitude and the quantity of load cycles. The accumulated strain rises with the number of loading cycles, indicating a decline in soil strength. Degradation curves can therefore be used to evaluate a soil's capacity to withstand cyclical loads, such as those brought on by seismic activity. Degradation curves were calculated according to the fifth equation (Vardanega & Bolton, 2013):

$$\frac{G}{G_{max}} = \frac{1}{1+\left(\frac{\gamma}{\gamma_{ref}}\right)^{0.736}} \tag{5}$$

Where $\frac{G}{G_{max}}$ represents each node degradation curve, γ is the shear strain, and γ_{ref} is the reference shear strain at an effective confining pressure.

2.1.2.2. Seismic response analysis

All geotechnical sites share the characteristic of having heterogeneous soil deposits, which poses a challenge for predicting their dynamic behavior. In this sense, homogenizing these deposits may be an option to simplify modeling and analysis of their response to dynamic loads. Figure 7 shows a conceptual representation of the homogenization process of a variable layered column of soil. This homogeneous model, by using just one representative parameter, is intended to get a precisely approximation to the dynamic response expected for the heterogeneous model.

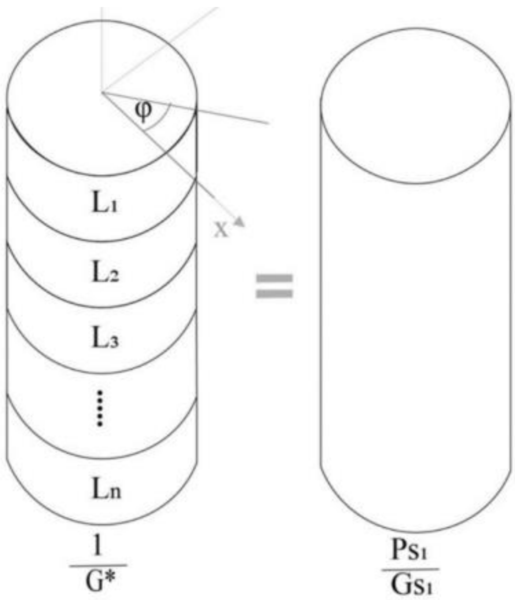

Figure 7. Conceptual representation of a homogeneous model based on a heterogenous layered deposit (Pua L., et al, 2021).

For composite materials, Hashin & Shtrikman suggest that homogenization should rely between bounding limits, which assumes homogeneity and elasticity (1963). Therefore, three homogeneous models where proposed based on the sixth equation:

$$G_L < G < G_U \tag{6}$$

Where G is the G_{max} of the composite material (heterogeneous model), G_L and G_U are the lower and upper bounds respectively of the shear modulus for the homogeneous model. Additionally, there was proposed a Corrected Limit, which is a combination between both bounds and tries to better simulate the heterogeneous model.

Two vertical analysis cuts were made for this purpose at 3 m and 25 m from the deposit's left side. The properties displayed above were taken as a soil column for each of these cuts. Through a finite element analysis, these properties were exported to OpenSees. The model proposed can be understood as springs connections. This springs analogy, assumes continuity of forces (Lower Limit), continuity of deformations (Upper Limit), and a proposed model which considers continuity of deformations and continuity of forces for G_{max} and γ_{ref} (Corrected Limit). The assembly of the model's nodes is shown in figure 8, with a discretization of 4 nodes per layer, and 1 m length per layer.

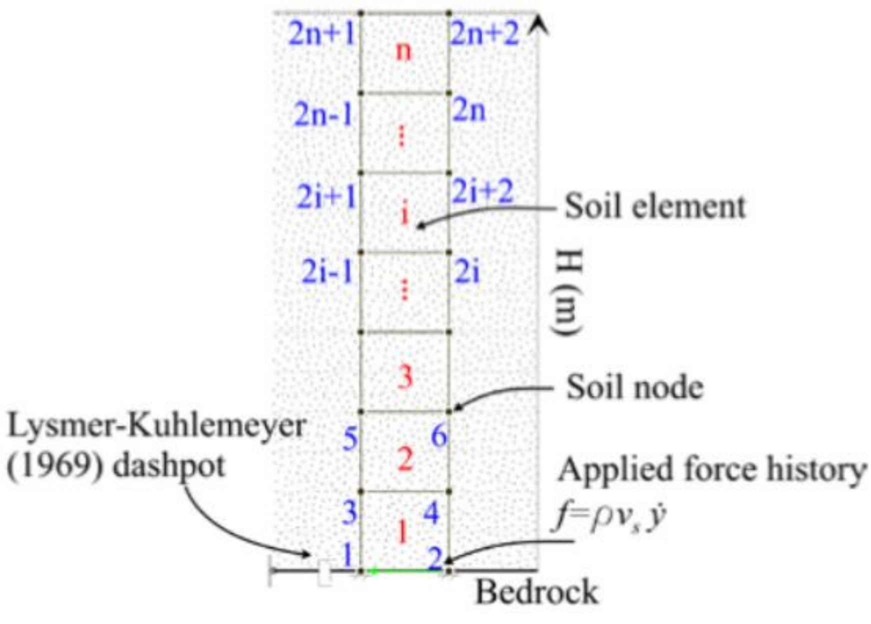

Figure 8. Conceptual representation of the finite element one-dimensional wave propagation model (Ibagon L., et. al., 2023).

Along each soil column, represented as each one of the cuts mentioned before, a one-dimensional wave propagation model was run (McGann & Arduino, 2011). For the dynamic analysis, a seismic signal from rock was used as the input, and the response on the surface was determined by analyzing how the signal spread throughout the entire stratum. For the dynamic analysis of the heterogeneous and homogeneous models, two earthquakes were collected. A recording of the 1992 earthquake in Landers, California's accelerogram was introduced in the model, which had a magnitude of 7.28 Mw. Figure 9.a shows the ground motion acceleration registered at Lucerne Station, which measured a peak ground acceleration of 0.727 g (U. Berkley). Additionally, figure 9.b shows the Fast Fourier Transformation, which shows the frequential content of the signal. It has a very varied frequential content, with a peek value at approximately 12 Hz.

a) b)

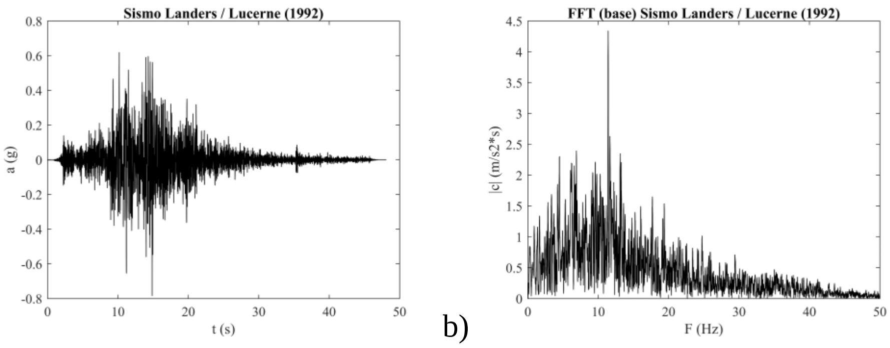

Figure 9. Landers earthquake registered at Lucerne Station. a) Ground motion acceleration and b) Fast Fourier Transformation. (U. Berkley).

The Loma Prieta earthquake in San Francisco in 1989 was the second seismic signal examined within the one-dimensional propagation model. It had a magnitude of 6.93 Mw (U. Berkley). Figure 10.a shows the ground motion acceleration registered at Gilroy Array #1 Station, which measured a peak ground acceleration of 0.433 g (U. Berkley). Additionally, figure 10.b shows the Fast Fourier Transformation, which shows the frequential content of the signal. It has a peek value at approximately 2.5 Hz.

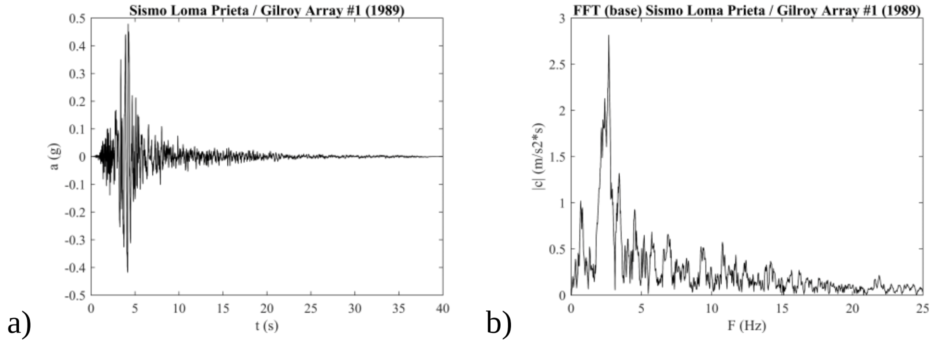

Figure 10. Loma Prieta earthquake registered at Gilroy Array #1 Station. a) Ground motion acceleration and b) Fast Fourier Transformation. (U. Berkley).

3. RESULTS AND DISCUSSION

The one-dimensional wave propagation model was simulated for each one of the cuts, and for each one of the earthquakes shown (four models). Next, it is shown results for the Loma Prieta earthquake, and the cut made in the middle of the deposit (25 m). In the following figures, the red line represents the dynamic response for the heterogeneous model, meanwhile the blue, black, and pink lines represent the Lower Limit, Upper Limit and Corrected Limit respectively. Results for the Loma Prieta earthquake at 3 m can be found in appendix A, for the Landers earthquake at 3 m can be found in the appendix B, and finally the results for the Landers earthquake at 25 m can be found in appendix C.

The surface motion acceleration for the four models is shown in figure 11. On surface, the maximum acceleration has a value around 4 m/s2. Homogeneous models matches the peaks of the heterogeneous model.

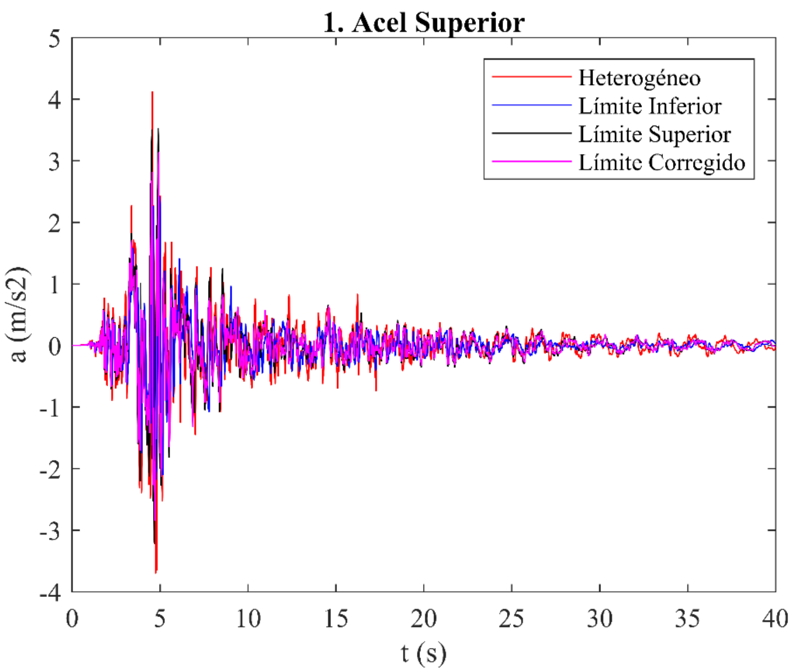

Figure 11. Surface motion acceleration for the four models.

The frequency content, displayed by a Fast Fourier Transformation of the acceleration signal, is shown in figure 12. Homogeneous models manage to capture to a great extent frequencies from the real layered deposit. Almost all peaks match for the four models, except for frequencies around 14 Hz, where homogeneous models underestimate the frequency content.

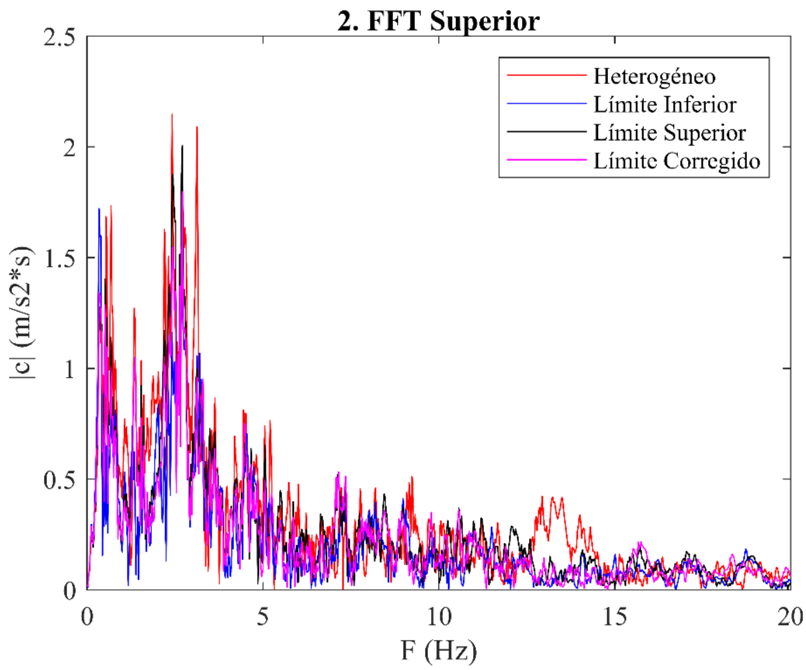

Figure 12. Fast Fourier Transformation at the surface for the four models.

Moreover, the spectral acceleration at surface for the four models is shown in figure 13. Two main things can be highlighted from this graph. First, homogeneous models proposed had the exact same spectral acceleration shape, at least for all values until the plotted 3 s maximum period at the x-axis. This represents that these models manage to correctly simulate the behavior of the heterogeneous model. Second, for small structural periods, all models get almost the same acceleration, but for periods from 0.7 s to 1.7 s, homogeneous models underestimate the acceleration, and the graphs separate a little.

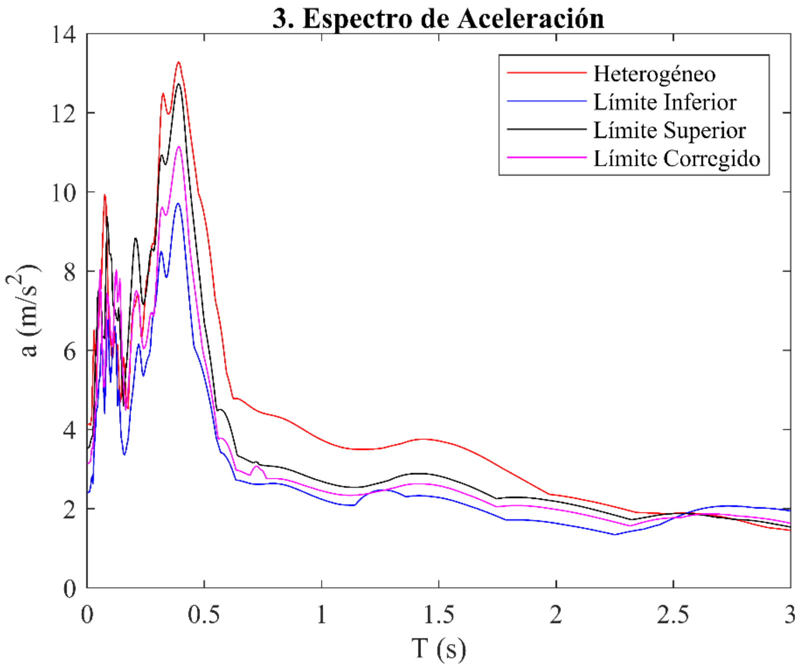

Figure 13. Spectral acceleration at surface for the four models.

For a better result analysis, there was developed a normalized spectral acceleration at surface graph, shown in figure 14. For this, the homogeneous spectral acceleration was divided into the heterogeneous spectral acceleration. This means that, for values near one in the y-axis, the models are closest to real heterogeneous values, and therefore, the proposed models are more accurate by getting a good approximation of the dynamic response. The portion of the lines above one represents an overestimation in the spectral acceleration, meanwhile values below represent a sub estimation in the models. In this case, the Lower Limit results get values far away from one, which represents larger percentage errors. That is why the blue line is not plotted in figure 14. Additionally, the Corrected Limit has a maximum of 40% error, meanwhile the superior limit has a maximum of 30% error. As mentioned before, the maximum error occurs for periods from 0.7s to 1.7 s.

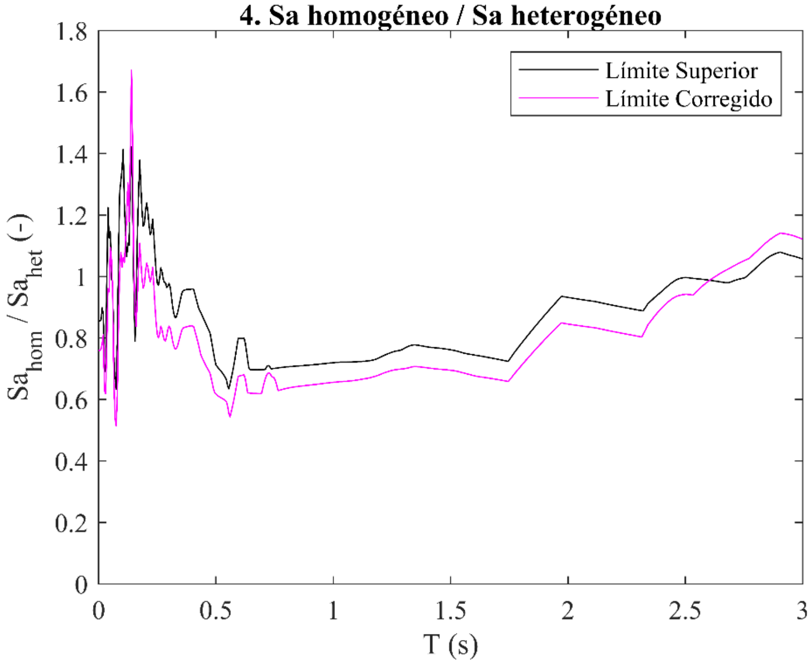

Figure 14. Normalized Spectral acceleration at surface for the two homogeneous models.

From figures shown in appendixes A, B, and C, it can be seen a tendency in the results, with almost the exact same behavior and error percentages of the models. The results for the Loma Prieta earthquake simulation at 25 m have the same tendency, and error percentages as the 3 m cut showed in the appendix A. This suggests that the proposed methodology is accurate and seems to be suitable for use through the whole deposit. This finding was supported by the analysis of the additional earthquake input of Landers, found in Appendix sections B, and C for 3 m and 25 m respectively. These analyses' findings demonstrated that the suggested methodology is reliable and capable of correctly predicting the ground motion response for various earthquake inputs and frequencies. Additionally, the methodology can capture the spatial variability of soil characteristics and how it affects the ground motion response.

4. CONCLUSION

In conclusion, MATLAB and OpenSees have been used to create a computational model for the homogenization of a random field in seismic wave propagation. This research presents the seismic response analysis of various homogeneous soil deposit models, compared to a layered one. For the conditions examined in this study (fine clayey soils, with a liquid limit range of 87% to 348%, for an autocorrelation length of 4 m, and for earthquakes with predominant frequencies of 2.5 Hz and 12 Hz), the computational model proved to be useful. A significant issue in geotechnical engineering is the homogenization of a random field, and this study has produced an important tool to address this issue. Nevertheless, during the simulation of vibration periods, the model's shortcomings were discovered. For periods in the range of 0.7 s to 1.7 s, the homogeneous model has a maximum percentage of error of 40% for the corrected limit, while the superior limit has a 30% of error. The Corrected Limit has proven to obtain larger error percentages, so those results and model was discarded.

To better comprehend these restrictions and raise the model's accuracy in these circumstances, more research is required. In general, this study has shown that it is possible to homogenize a random field in seismic wave propagation using a computational model. It has also drawn attention to the need for more study to enhance the model's precision and broaden its applicability under various circumstances. It is advised that future research will examine the impact of various parameters, such as soil variability (introducing different correlation lengths), more vertical cuts analysis through the random field to discard position effects, more seismic waves modeled, to cover a much wider range of frequential contents, to rule out probable limitations to the model proposed.

The findings of this study imply that the suggested methodology can be applied for seismic hazard assessment and earthquake-resistant building design, important in seismic vulnerable countries like Ecuador. The results of this study demonstrate the significance of considering the spatial variability of soil properties in a dynamic analysis and the requirement for accurate and dependable methods to account for it. An accurate homogenization in determining the dynamic seismic response of structures, can reflect on important economic savings. This due to expensive dynamic tests, that are done to analyze shear wave velocity in a deposit.

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APPENDIX A: LOMA PRIETA, 3M.

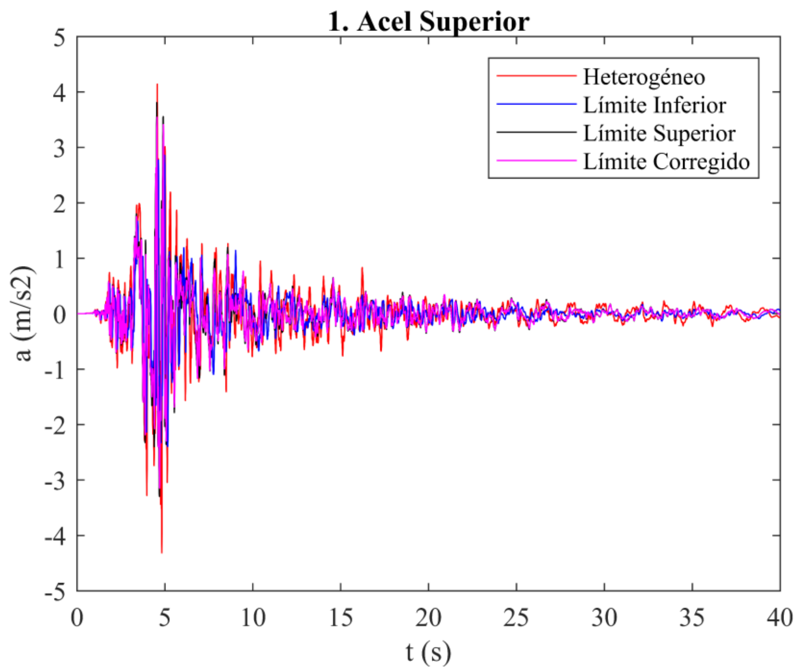

Figure 15. Loma Prieta, 3m. Surface motion acceleration for the four models.

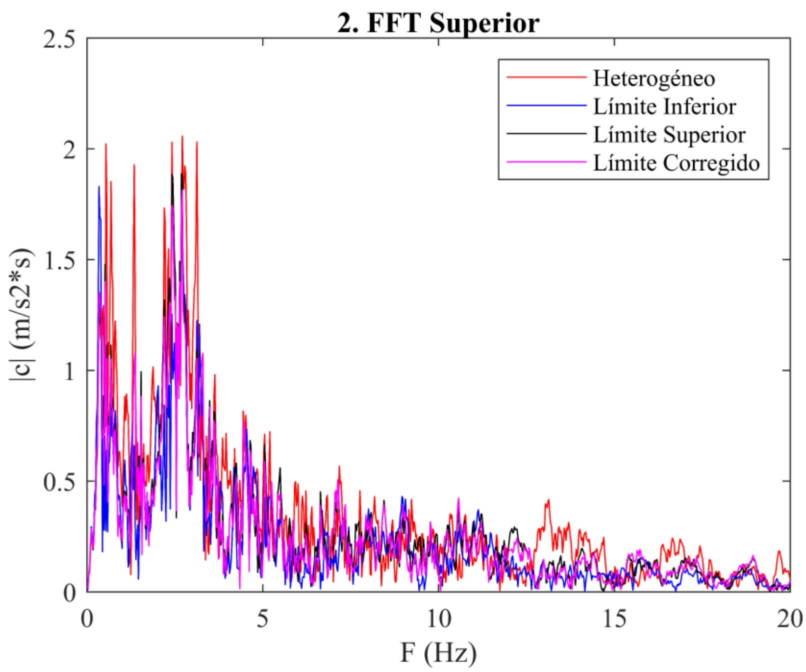

Figure 16. Loma Prieta, 3m. Fast Fourier Transformation at the surface for the four models.

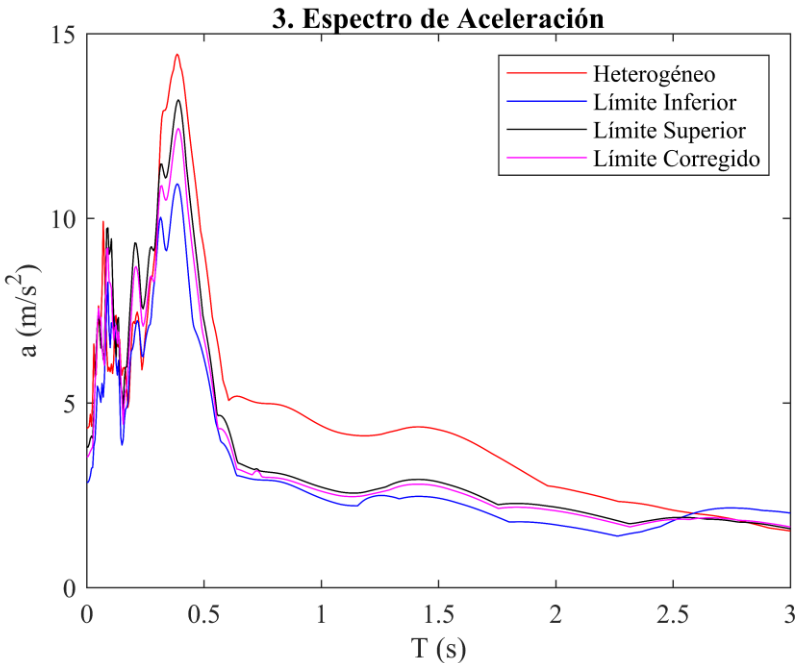

Figure 17. Loma Prieta, 3m. Spectral acceleration at surface for the four models.

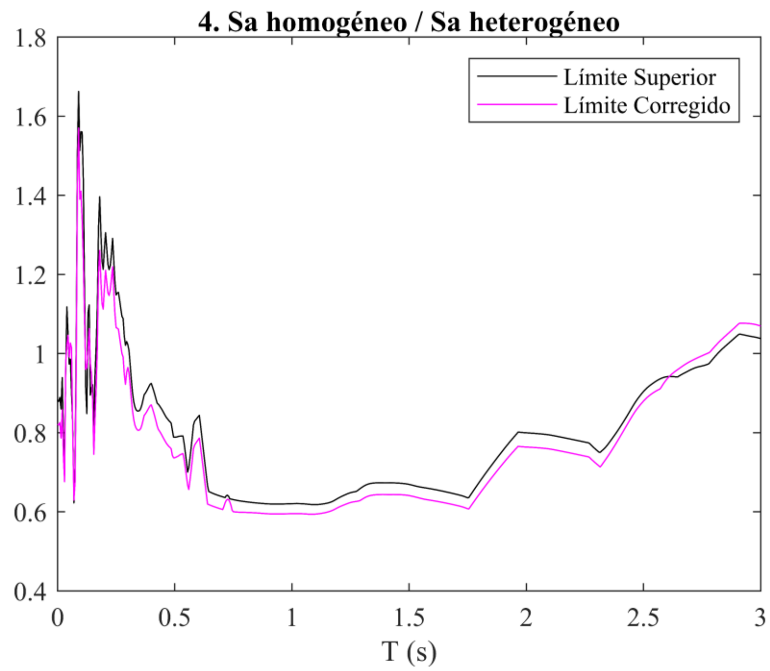

Figure 18. Loma Prieta, 3m. Normalized Spectral acceleration at surface for the two homogeneous models.

APPENDIX B: LANDERS, 3M.

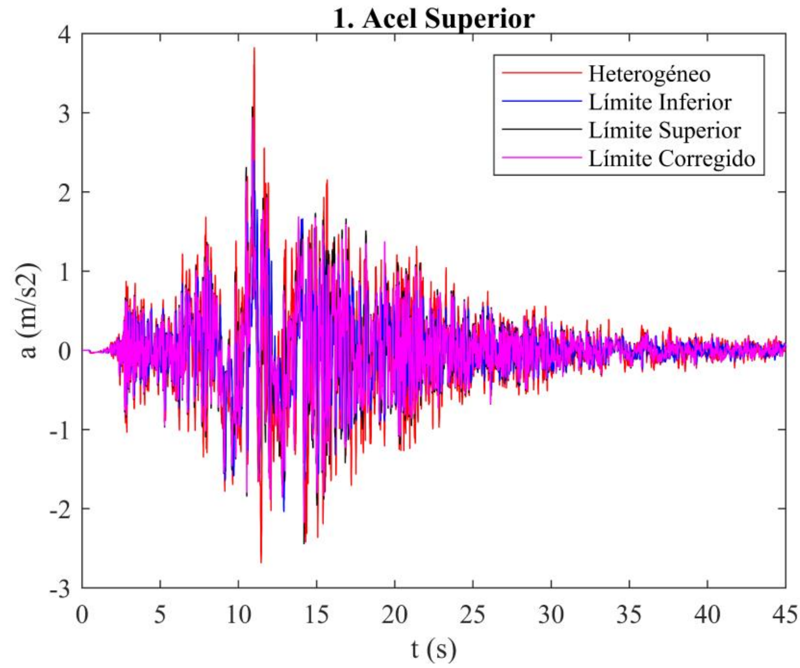

Figure 19. Landers, 3m. Surface motion acceleration for the four models.

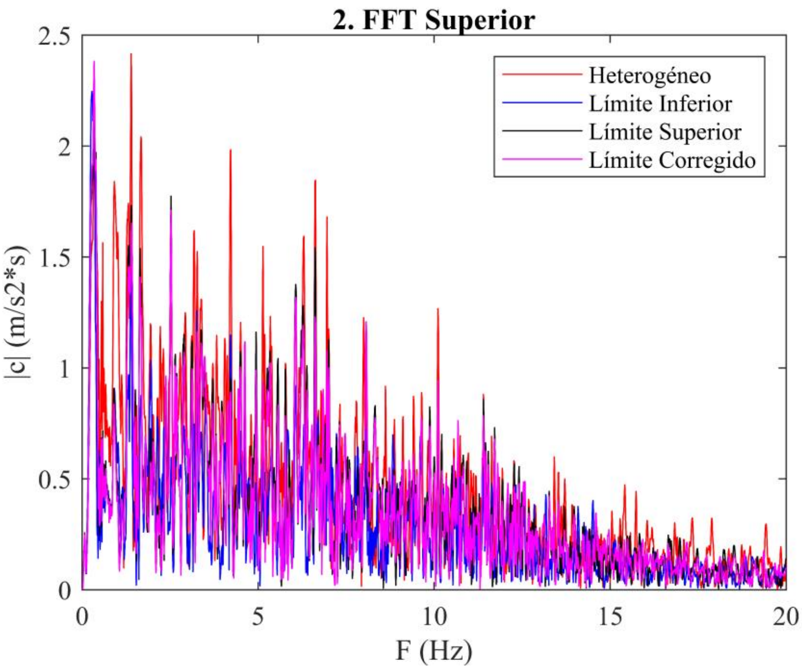

Figure 20. Landers, 3m. Fast Fourier Transformation at the surface for the four models.

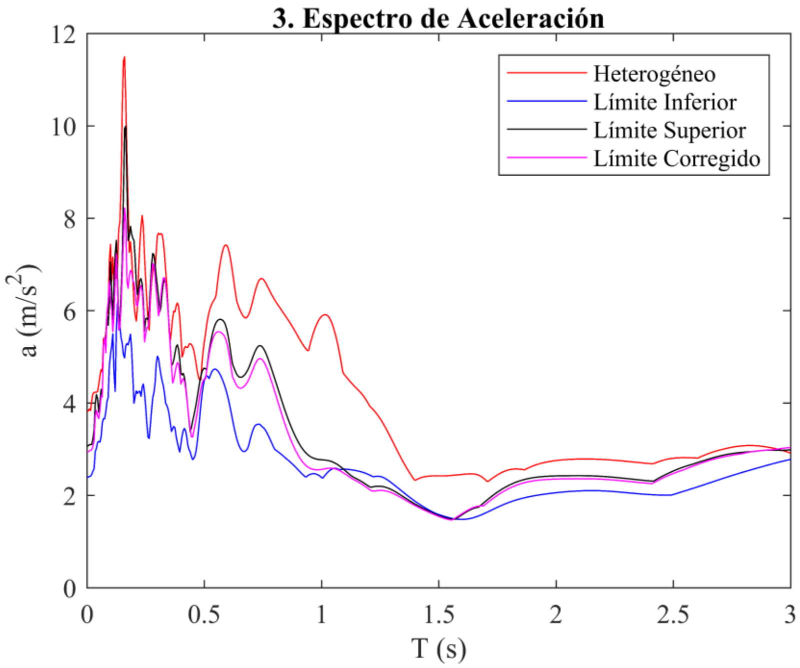

Figure 21. Landers, 3m. Spectral acceleration at surface for the four models.

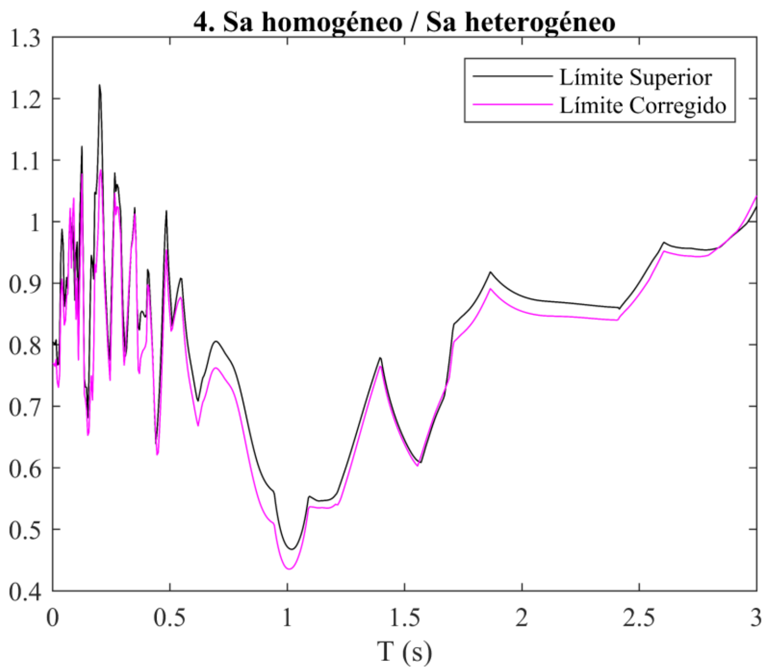

Figure 22. Landers, 3m. Normalized Spectral acceleration at surface for the two homogeneous models.

APPENDIX C: LANDERS, 25M.

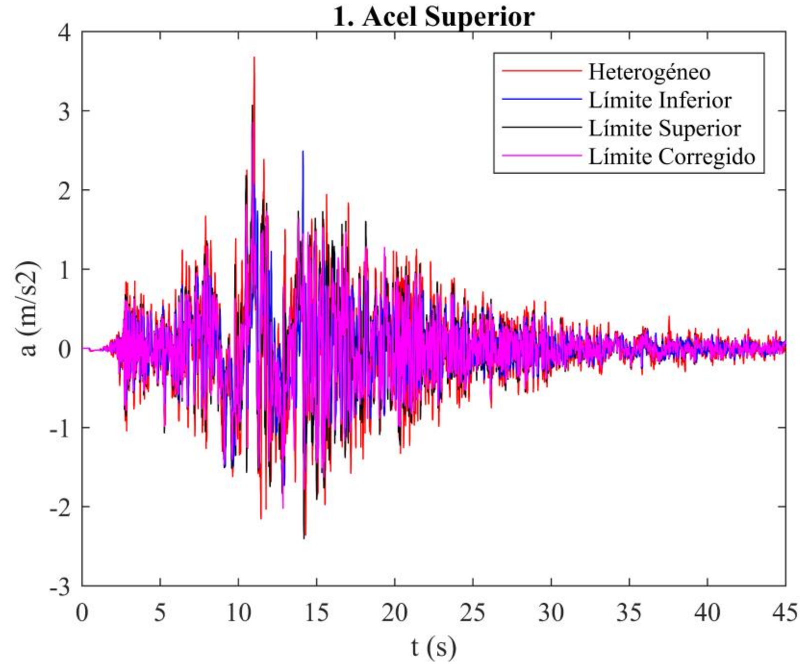

Figure 23. Landers, 25m. Surface motion acceleration for the four models.

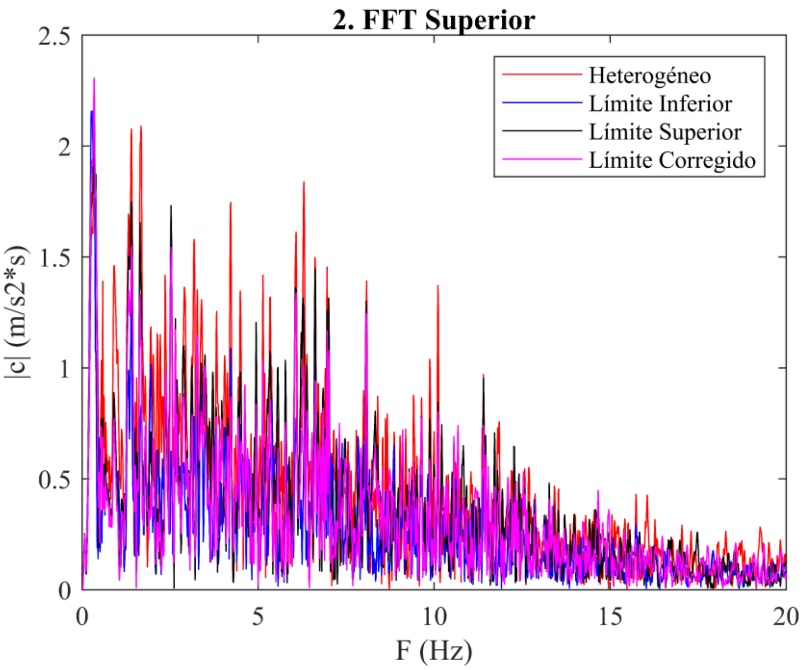

Figure 24. Landers, 25m. Fast Fourier Transformation at the surface for the four models.

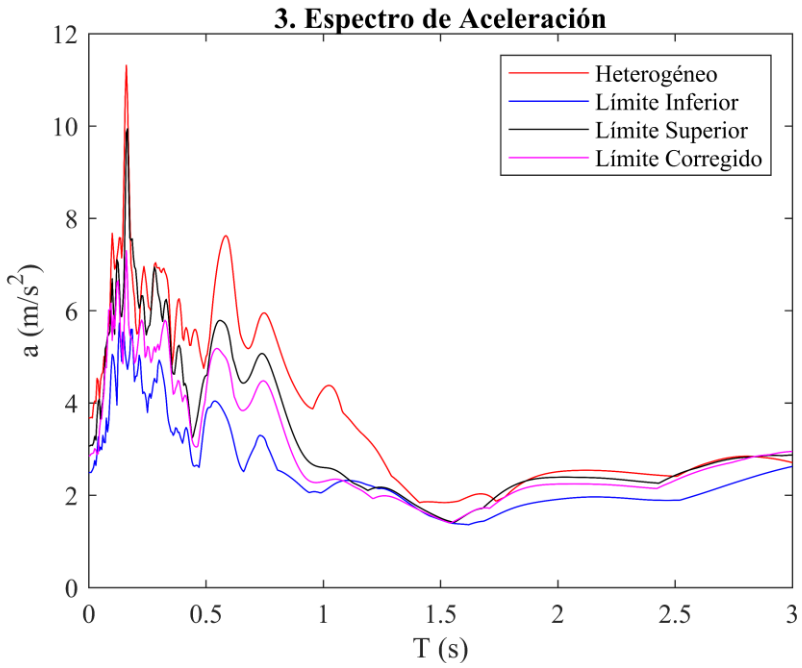

Figure 25. Landers, 25m. Spectral acceleration at surface for the four models.

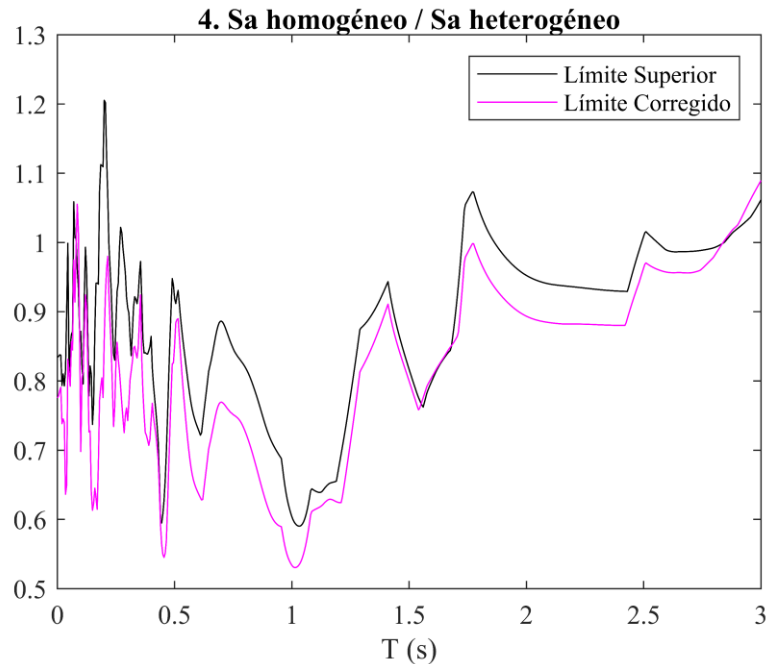

Figure 26. Landers, 25m. Normalized Spectral acceleration at surface for the two homogeneous models.