UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

An equivalent model for a multilayer rammed earth wall

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Ingeniería Civil

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RESUMEN

El modelado con elementos finitos requiere de tiempo y una gran cantidad de datos conocidos, es por esta razón que se recurre a modelos simplificados. La investigación trata sobre dos muros de 2.5m de longitud por 2.4 de altura por 0.3 y 0.5 m de espesor que serán expuestos una señal sísmica en un modelo multicapa. Las propiedades utilizadas en el modelo multicapa se homogeneizarán para obtener límites basados en la teoría de los materiales compuestos para simplificarlo. A partir de estos resultados, se vuelven a simular los modelos con un modelo equivalente y se compararán los resultados de la frecuencia de vibración natural y el desempeños bajo la carga sísmica. Como conclusiones se tiene que el tiempo optimizado es sumamente menor. Además, los resultados del límite superior se asemejan más a los resultados del modelo multicapa. Se recomienda su uso para siguientes investigaciones por su optimización de tiempo y recursos.

Palabras clave:

Muro de tierra apisonada, succión, rendimiento dinámico, modelo multicapa, modelo equivalente, límite superior, y límite inferior.

ABSTRACT

Modeling with finite elements requires time and a large amount of known data, it is for this reason that simplified models are used. The investigation deals with two walls 2.5 m long by 2.4 high by 0.3 and 0.5 m thick that will be exposed to a seismic signal in a multilayer model. The properties used in the multilayer model will be homogenized to obtain limits based on the theory of composite materials for simplicity. From these results, the models are simulated again with an equivalent model and the results of the natural vibration frequency and the performance under seismic loading will be compared. As conclusions, we have that the optimized time is extremely less. In addition, the results of the upper limit are more similar to the results of the multilayer model. Its use is recommended for further investigations due to its optimization of time and resources.

Keywords:

Rammed earth wall, suction, dynamic performance, multi-layer model, equivalent model, upper bound, and lower bound.

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INTRODUCCIÓN

In the study of soils and based on the theories made by Terzaghi, it is assumed that the soil is a homogeneous material (Xiao, 2015), but it is not (Pua et al., 2021). For greater accuracy in the results, it is preferable to analyze the behavior of soils using as much data as can be collected. The problem is that the only way to analyze with so much data is through finite element modeling. The problems a researcher faces when dealing with these models are the time taken for each simulation and the difficulty of collecting the required amount of data.

The use of finite elements in the field of Geotechnics is frequent. For example, (Monforte et al., 2017) use the Particle Finite Element Method (PFEM) to simulate geotechnical problems such as "Strip footing on clay" which deals with penetrating a rough, stiff footing into the ground. Another example is (Liu et al., 2018) that used finite elements to analyze the stability of a Rock-soil slope to obtain a safety factor. Finally, another case that uses this method is (Manzoli et al., 2018) that uses an orthotropic interface damage model to simulate the drainage process in soils.

The examples presented above demonstrate the use of finite element modeling today. It is for this reason that it is proposed to find an equivalent model that optimizes the collection of input data and simulation times. In addition, it is expected to propose, apply, and compare results of a method of homogenization of physical properties of the soil. These objectives will be achieved with the help of the theory of composite materials proposed by (Hill, 1967).

A rammed earth wall is a new method of building structural walls. These are composed of a mixture of soil compacted by layers of approximately 15 cm. These layers are stacked until they reach the desired height (Nowamooz & Chazallon, 2011). This research is divided into materials and methods, results and discussions, conclusions, and

Bibliographic references. The methodology is divided into 3 stages to better differentiate each step taken.

DESARROLLO DEL TEMA

Materials and methods

Materials

As this was purely a numerical analysis, the materials used were the data obtained from past research (Villacreses et al., 2021) and the programs. The properties recollected describe a "fine-grained compacted soil, classified as high plasticity clay (C.H.) according to the Unified Soil Classification System (USCS), with a liquid limit of 87% and a plastic limit of 37%" (Villacreses et al., 2021).

Methods

The methodology is divided into three sections that are described below. The first stage objective is to determine the mechanical performance and the natural translational frequency along the strong direction of a wall model made of three and five layers with different saturation percentages. The second stage is about using a technique of homogenization based on the (Hashin & Shtrikman, 1963) theory that was already approved by (Pua et al., 2021). Once that these moduli were obtained, in stage 3, it is assigned to the model (that was multilayered and now has only one layer) a unique value of bulk density and shear modulus. Finally, there are going to be evaluated two parameters. The first one is the natural translational frequency along the strong direction of the wall and the second one is the mechanical performance of the equivalent model exposed to a seismic signal. These two parameters are going to be compared with the results of the multilayered models.

Stage 1: Simulate the mechanical performance of a rammed earth section (multi-layer).

The results previously obtained by (Villacreses et al., 2021) are the properties of the walls describing the suction and water content for each mathematical model. The multilayer models were developed to compute the performance of earthen structure that has a hydraulic gradient within their thickness. The investigation conducted by Villacreses (Villacreses et al., 2021) used a multilayered model to compute the performance under drying and wetting seasons. This investigation modeled two walls geometries (2.5 * 2.4 * 0.3 m and 2.5 * 2.4 * 0.5 m) that were the same as the investigation conducted by (Q.-B. Bui et al., 2009, 2011, 2016; T.-T. Bui et al., 2016; El-Nabouch et al., 2017). The first model was made of 2400 elements while the second of 4000 elements. The elements had three degrees of freedom in each node.

The data input for each model is the shear modulus, the bulk density, and the bulk modulus. Furthermore, the calculations through the simulation of finite elements of the natural translational frequency along the strong direction of the wall and the modal shape were for different geometries, at different times associated with the assigned moisture content (Villacreses et al., 2021). The models were developed in Open Sees.

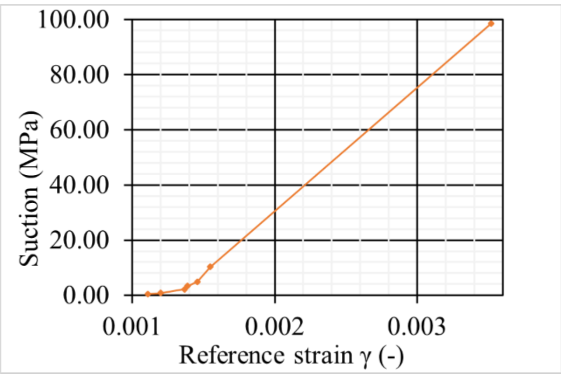

Fig. 1. Shear modulus degradation curve.

To calculate the dynamic behavior at 388 hours of the walls, the Loma Prieta Gilroy N◦1 E-W 1989 seismic acceleration signal was introduced. For this calculation, another input is obtained with Fig. 1. This figure follows Eq. (1) and is called the degradation curve.

$$\frac{G}{G_{max}} = \frac{1}{1+\frac{\gamma'}{\gamma_r{}'}} \quad (1)$$

The investigation of (Villacreses et al., 2021) has the data used to draw the shear modulus degradation curves for different suction conditions. Once acquired the information, the curve was adjusted to compute the reference strain which is the value wanted. For each layer of the model, there is a percentage of moisture that corresponds to a value of suction. With the suction value, the shear modulus reference was interpolated. This helps to acquire the normalized curve per layer which is necessary for the earthquake simulation.

Stage 2: Homogenization to estimate the shear modulus and bulk density

The research of (Pua et al., 2021) proposes the equations for the homogenization of materials for a heterogeneous soil, while in this research, the soil is the same through all the bodies with different water content. The assumption made was that the model is layered on the same local scale to simplify the cored samples' mechanical behavior (Pua et al., 2021). The data that is going to be homogenized is the shear modulus and bulk density.

It is important to know that composite materials' bounding limits proposed by (Hashin & Shtrikman, 1963) will be used. It will result in an upper and lower bound. Composite material has elasticity constants for their components. These components and the stored strain energy are used to evaluate the bounds (Pua et al., 2021).

The same method is used to generate shear modulus and bulk density limits. It is defined as the upper limits with the subscript U while the lower limits will have the subscript L. Thus, the symbols are as follows:

G_U: Shear modulus upper bound

ρ_U: Bulk density upper bound

G_L: Shear modulus lower bound

ρ_L: Bulk density lower bound

The bounds proposed by (Hashin & Shtrikman, 1963) and verified by (Pua et al., 2021) are used to compute the limits. The upper bound (G_U) and lower shear modulus bound (G_L) were computed using Eq. (2) and (5) respectively. The model requires the computation of two additional parameters. β_1 is the first parameter that depends on $k_{Si}^{min/max}$ that is the minimum or maximum value of the bulk modulus that each layer of the composite material has. Also depends on the minimum or maximum value of G according to what is needed. The second parameter is B_1 that depends on ν_r which is the percentage of participation of the layer in the total composite material. Additionally, G_{Si} or ρ_{Si} must be considered according to what is wanted.

$$G_U = G_{Si}^{max} + 0.5\frac{\beta_1}{1+\beta_1 B_1} \quad (2)$$

$$G_L = G_{Si}^{min} + 0.5\frac{\beta_1}{1+\beta_1 B_1} \quad (5)$$

$$\beta_1 = \frac{3\cdot\left(k_{Si}^{max}+2G_{Si}^{max}\right)}{5G_{Si}^{max}\cdot\left(3k_{Si}^{max}+4G_{Si}^{max}\right)} \quad (3)$$

$$\beta_1 = \frac{3\cdot\left(k_{Si}^{min}+2G_{Si}^{min}\right)}{5G_{Si}^{min}\cdot\left(3k_{Si}^{min}+4G_{Si}^{min}\right)} \quad (6)$$

$$B_1 = \sum_{r=2}^{r=n}\frac{\nu_r}{\frac{1}{2\cdot\left(G_{Si}-G_{Si}^{max}\right)}-\beta_1} \quad (4)$$

$$B_1 = \sum_{r=2}^{r=n}\frac{\nu_r}{\frac{1}{2\cdot\left(G_{Si}-G_{Si}^{min}\right)}-\beta_1} \quad (7)$$

The same equations are used to calculate bulk density limits by changing rho where the shear modulus has been. The adapted equations that help to calculate these bounds are (8) – (13) (Hashin & Shtrikman, 1963).

$$\rho_U = \rho_{Si}^{max} + 0.5\frac{\beta_1}{1+\beta_1 B_1} \quad (8)$$

$$\beta_1 = \frac{3\cdot\left(k_{Si}^{max}+2\rho_{Si}^{max}\right)}{5\rho_{Si}^{max}\cdot\left(3k_{Si}^{max}+4\rho_{Si}^{max}\right)} \quad (9)$$

$$B_1 = \sum_{r=2}^{r=n} \frac{\nu_r}{\frac{1}{2\cdot\left(\rho_{Si}-\rho_{Si}^{max}\right)}-\beta_1} \quad (10)$$

$$\beta_1 = \frac{3\cdot\left(k_{Si}^{min}+2\rho_{Si}^{min}\right)}{5\rho_{Si}^{min}\cdot\left(3k_{Si}^{min}+4\rho_{Si}^{min}\right)} \quad (12)$$

$$\rho_L = \rho_{Si}^{min} + 0.5\frac{\beta_1}{1+\beta_1 B_1} \quad (11)$$

$$B_1 = \sum_{r=2}^{r=n} \frac{\nu_r}{\frac{1}{2\cdot\left(\rho_{Si}-\rho_{Si}^{min}\right)}-\beta_1} \quad (13)$$

Stage 3: Simulate the mechanical performance of a rammed earth section with homogenized properties.

The equivalent model has the same dimensions, but with larger internal elements than before. Having this new size of elements means that there are fewer elements in each wall. In this case, the 30 cm and 50 cm thick are now composed of 200 elements each. That means that there is only one material for each wall (one layer). Moving on, as explained in stage 2, two-property limits are obtained which are used to generate the simulation in the program. Resulting in the natural translational frequency along the strong direction for the upper and lower limit (double the results). Besides, the dynamic behavior at 388 hours was calculated also with one layer and with the same seismic signal.

Results and discussions

Having the same models and changing their saturation, directly affects the structural rigidity of the body (Villacreses et al., 2021). This can be verified by having a different fundamental frequency of vibration in each simulation (Villacreses et al., 2021). Furthermore, Fig. 2, 3, 4, and 5 show that there is a convergence at a natural frequency at the beginning and the end of the wetting and drying process because all its layers have very similar physical properties, forming a homogeneous material (Villacreses et al., 2021). These results are the same as in the investigation of (Villacreses et al., 2021) since the data were taken from it.

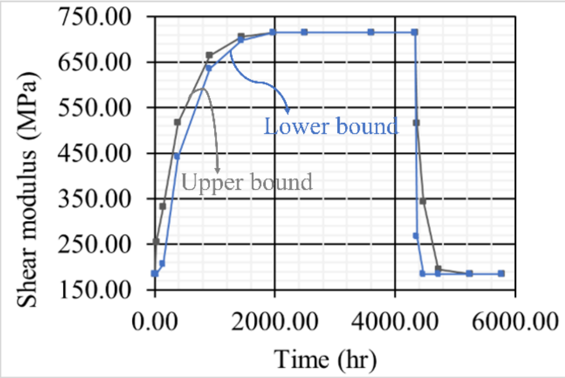

Fig. 2. Shear modulus of the 30 cm wall (upper bound in gray, lower bound in blue).

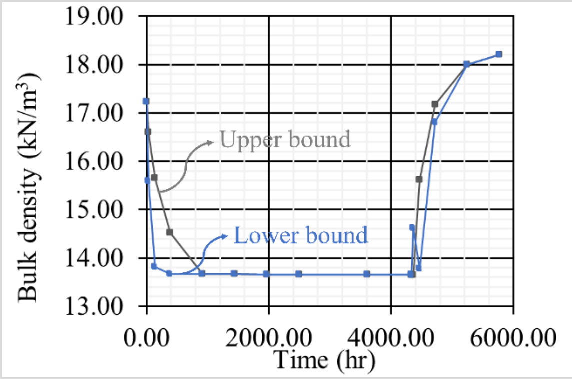

Fig. 3. Bulk density of the 30 cm wall (upper bound in gray, lower bound in blue).

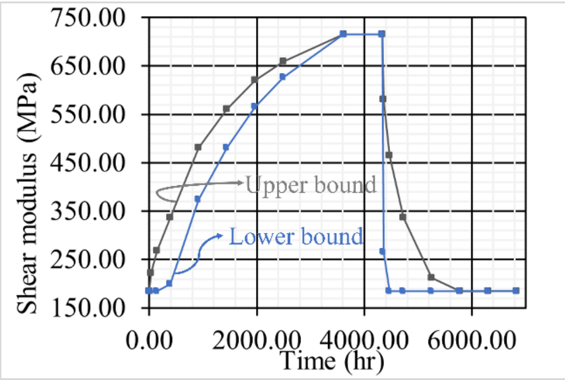

Fig. 4. Shear modulus of the 50 cm wall (upper bound in gray, lower bound in blue).

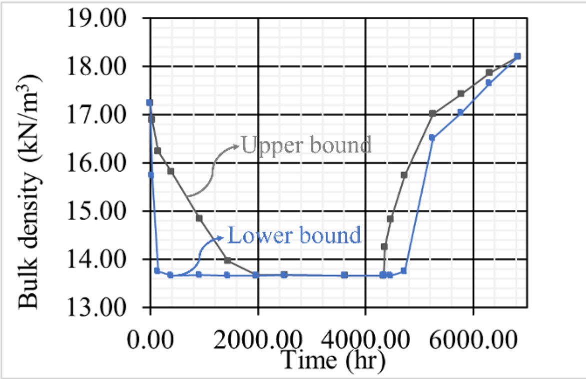

Fig. 5. Bulk density of the 50 cm wall (upper bound in gray, lower bound in blue).

The results of the homogenization of the physical properties of each model can be seen in figures 2, 3, 4, and 5. Besides, equations (2) - (13) that propose this method are not restricted by the considered correlation lengths (Pua et al., 2021) because they depend on the variation of the bulk modulus. In this case, they do not depend on the proportion of each layer with a certain percentage of suction, because being layers with the same dimensions, the proportion is the same.

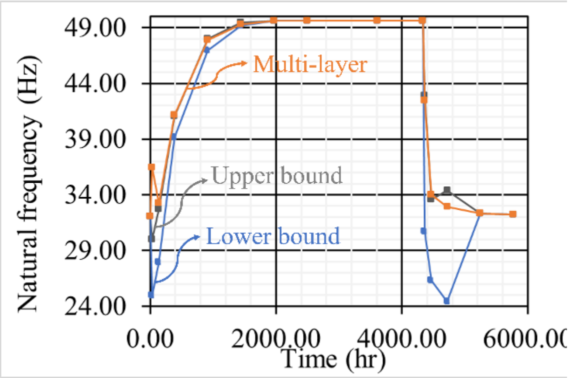

Fig. 6. Evolution over the time of the translational vibration mode for the 30 cm wall (multi-layer in orange, upper bound in gray, lower bound in blue).

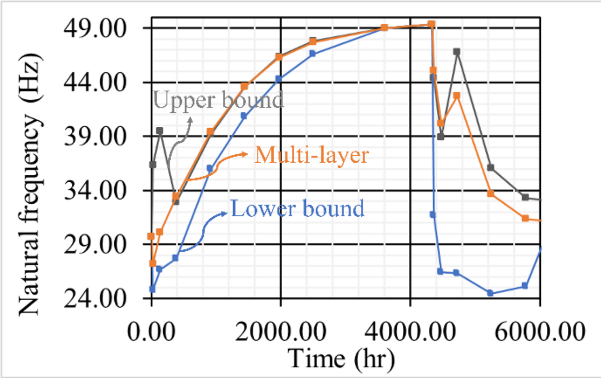

Fig. 7. Evolution over the time of the translational vibration mode for the 50 cm wall (multi-layer in orange, upper bound in gray, lower bound in blue).

In Fig 6 and 7, the results of the fundamental frequency in mode 3 for multi-layer and each limit are observed. The figures show that for both walls, the limit that results most like the multi-layer has been the upper bound. Considering the time saved by running the equivalent models (20 seconds) compared to the multi-layer models (8-36 hours) and the proximity of results, this method is worth considering. In consequence, the simulation of the earthquake is going to be compared with the upper bound.

As seen in Fig 6 and 7, the results of the natural frequency of the 30 cm wall are closer between the upper bound model and the multi-layer model than the 50 cm wall is because the proportion of the number of elements is 1/12 and 1/20 respectively. These proportions show that the elements of the 50 cm wall are larger than the 30 cm wall and if the objective is to have closer results using the equivalent model, you need to use smaller elements. The number and size of the elements depend on what results are the aspired. If the elements are smaller, the result will be more exactly to the real structure, but it would overly lengthy the waiting. If the elements are bigger, the results are going to be the opposite of the previous case. Despite using the homogenization proposed, is recommended to use smaller elements for better results as was demonstrated by comparing the results from the two walls.

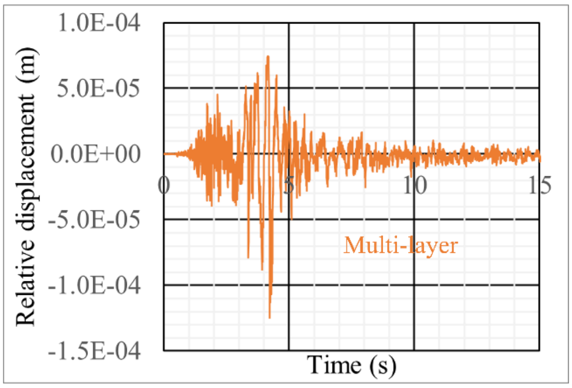

Fig. 8. Relative displacement response of the structures subjected to the Loma Prieta Gilroy N◦1 E-W earthquake of the 0.3 m wall for a multi-layer model.

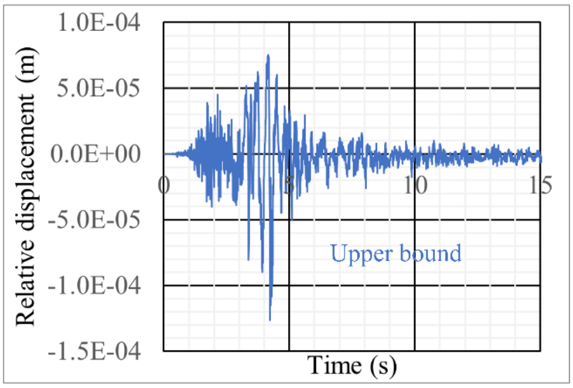

Fig. 9. Relative displacement response of the structures subjected to the Loma Prieta Gilroy N◦1 E-W earthquake of the 0.3 m wall for an equivalent model.

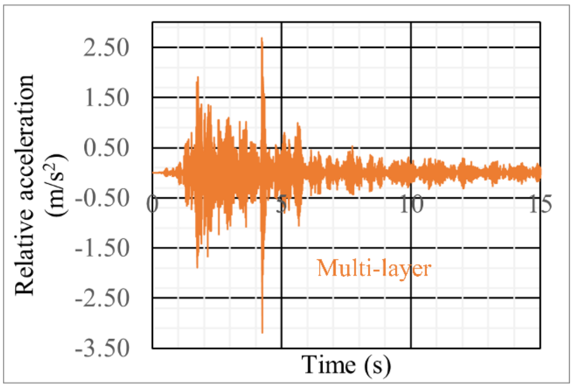

Fig. 10. Relative acceleration of the 0.3 m wall for a multi-layer model.

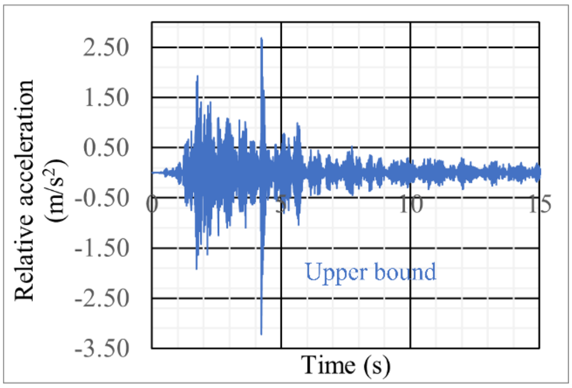

Fig. 11. Relative acceleration of the 0.3 m wall for an equivalent model.

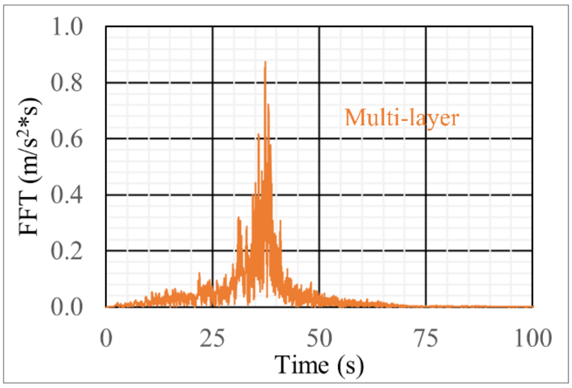

Fig. 12. Fast Fourier Transformation of the 0.3 m wall for a multi-layer model.

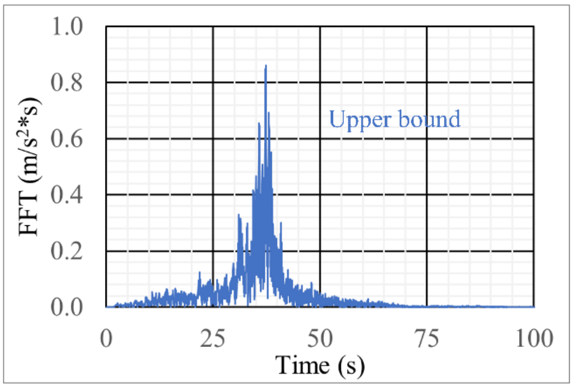

Fig. 13. Fast Fourier Transformation of the 0.3 m wall for an equivalent model.

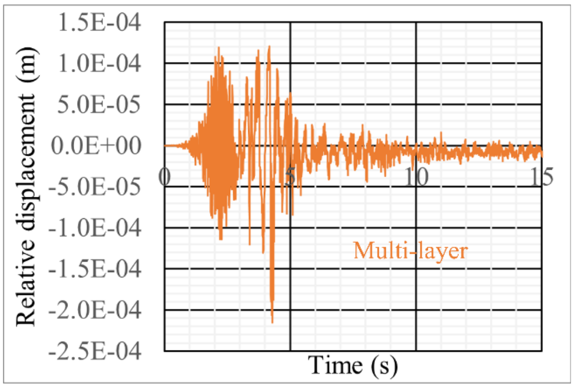

Fig. 14. *Relative displacement response of the structures subjected to the Loma Prieta Gilroy N◦1 E-W earthquake of the 0.5 m wall for a multi-layer model.*

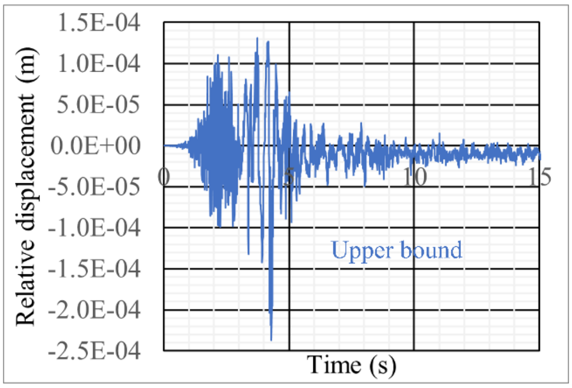

Fig. 15. Relative displacement response of the structures subjected to the Loma Prieta Gilroy N◦1 E-W earthquake of the 0.5 m wall for an equivalent model.

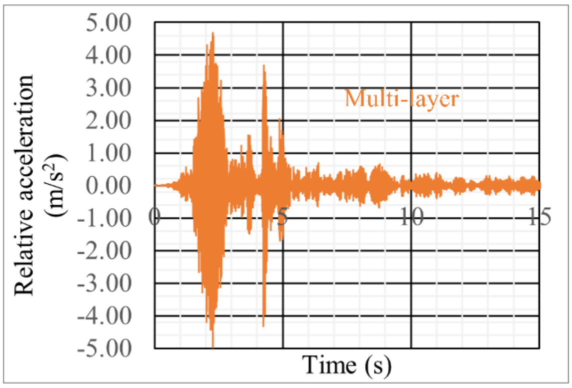

Fig. 16. Relative acceleration of the 0.5 m wall for a multi-layer model.

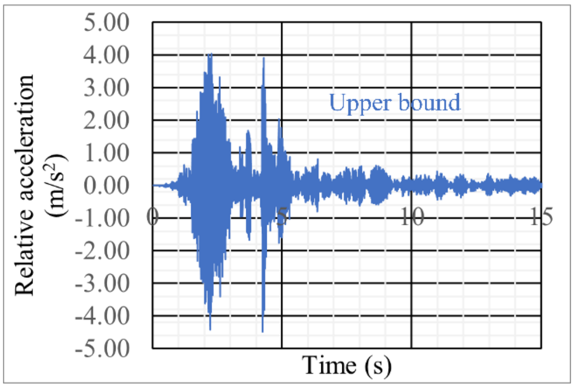

Fig. 17. Relative acceleration of the 0.5 m wall for an equivalent model.

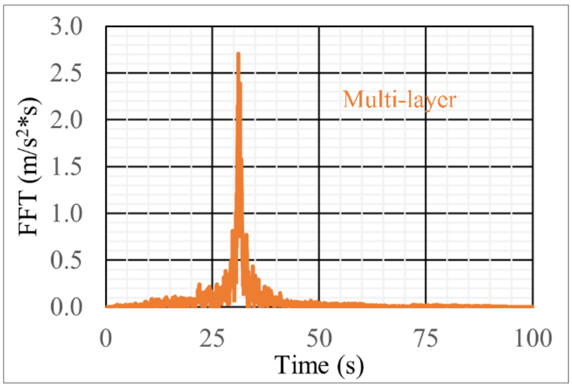

Fig. 18. Fast Fourier Transformation of the 0.5 m wall for a multi-layer model.

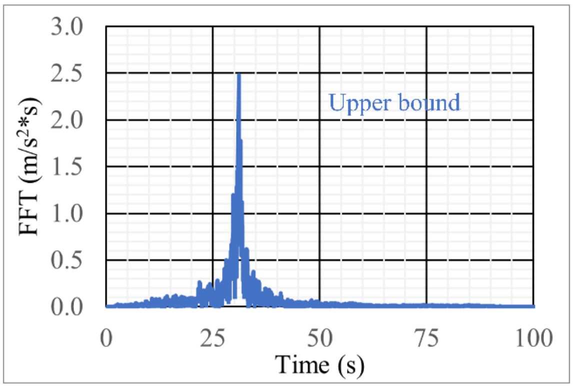

Fig. 19. Fast Fourier Transformation of the 0.5 m wall for an equivalent model.

Regarding the seismic response of the walls, the accelerogram Loma Prieta Gilroy No. 1 E-W (UC Berkeley, n.d.) was used for its frequency content and significant amplitude. Fig. 8 – Fig.13 show the results of the wall of 30 cm when it is exposed to the Loma Prieta Gilroy N◦1 E-W earthquake. Fig. 8 and 9 show the comparison of the relative displacement response and there is no difference. Fig. 10 and 11 reveal the relative acceleration and the outcomes are almost the same. Talking about Fig. 12 and 13 show its Fast Fourier Transformation (FFT) with the same outcomes as before. Along with this, Fig 14 – Fig. 19 expose the same results as Fig. 8 – Fig.13, but for the wall of 50 cm. To some extent, the results for the 50 cm wall are similar to the ones for the 30 cm wall, the are no significant differences between the upper bound model and the multi-layer model.

Table 1. Relevant results from the graphs obtained from the response from the earthquake for the 30 cm wall.

	30 cm wall		
	Multi-layer	*Upper bound*	*Percentage of difference*
Peak acceleration (m/s^2)	3.18793	3.22632	1.20 %
Predominant frequency (Hz)	37.34895	37.34895	-
Larger displacement (m)	1.247E-04	1.261E-04	1.12%

Table 2. Relevant results from the graphs obtained from the response from the earthquake for the 50 cm wall.

	50 cm wall		
	Multi-layer	Upper bound	*Percentage of difference*
Peak acceleration (m/s2)	4.96135	4.48118	9.68%
Predominant frequency (Hz)	31.05089	31.05089	-
Larger displacement (m)	2.152E-04	2.369E-04	10.08%

CONCLUSIONES

This study proposes a method to simplify a finite elements model composed of different layers with different moisture content to an equivalent model made of one layer. The models were rammed earth walls of 2.5m in length by 2.4 height by 0.3 and 0.5 m thickness, respectively. Numerical simulations are how they were verified if this reduction of properties covers enough information so that there are no significant changes in the behavior of the structure. The variation of the fundamental frequencies and the walls' mechanical dynamic performance under an earthquake were assessed with a finite element model simulation. The main conclusions are summarized as follows:

- The equivalent model using the upper bound has better results compared to the lower bound. This affirmation is supported by the similar results of the upper bound compared with the multi-layer model of the natural frequency and the dynamic performance.
- The results of the 30 cm wall are closer to the ones of the multi-layer wall than the ones of the 50 cm wall. This occurs due to the internal elements of the hugest wall are larger. Owing to there are more spaces that approximate properties.
- The time saved while running the equivalent models has no point of comparison with the multi-layer model. The analysis execution time was from 8 hours to 36 hours while the models with fewer elements took 20 seconds approximately.

This research shows another application for the theory proposed by (Hashin & Shtrikman, 1963), so it is being recommended to be considered for professional analysis. This method proposes a way of simplifying a model, considering all the properties and its proportions.

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