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A brief study of the influence of water content profile on compacted structures

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A brief study of the influence of water content profile on compacted structures

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RESUMEN

Esta investigación evalúa la influencia del contenido de agua en el rendimiento dinámico de estructuras de suelo compactado. El modelo de elementos finitos usa seis capas donde las propiedades de los materiales son asignados según el contenido de agua. LA investigación usa siete contenidos de agua para establecer el grado de saturación como función del espesor del muro. Las propiedades mecánicas de cada capa fueron asignadas de acuerdo al contenidode agua. Finalmente, las frecuencias y formas modales de la estructura fueron calculadas usando un modelo de elementos finitos. Los resultados mostraron un importante cambio en la rigidez de la estructura. El efecto fue analizado usando un espectro de respuesta en aceleraciones. Se lo realizó para mostrar la diferencia en la respuesta de la estructura debido al diferente contenido de agua. Los resultados sugieren que la estructura tiene diferente comportamiento sísmico al inicio de la construcción que cuando el muro llega al estado de humedad residual.

Palabras clave: Estructuras de suelo compactado, succión, efecto climático, perfil de contenido de agua, rendimiento dinámico.

ABSTRACT

This research assesses the influence of water content in the dynamic performance of rammed earth structures. The procedure uses a finite element model based on hypotheticals water content profiles. The finite element model uses six layers where materials were assigned based on the water content profile. The research uses seven water profiles to establish the saturation degree as a function of wall depth. The mechanical properties for each layer were assigned according to the water content profile. Finally, the frequencies and modal shapes of the structure were calculated using a finite element model. The results showed an important change in the structure stiffness. The effect was analyzed using a response spectrum of accelerations to show the difference of response due to the water content profile. The results suggest that the walls have different seismic behavior at the beginning of the construction and the residual water content state.

Key words: Rammed earth structures, suction, climate effect, water content profile, dynamic performance.

TABLE OF CONTENTS

INTRODUCTION 10
- Materials 12
- Methods: 13
- Results: 15

CONCLUSIONS 18

BIBLIOGRAPHIC REFERENCES 19

TABLE INDEX

Table 1 Final properties for the case four of water profile. 15

FIGURE INDEX

Figure 1. Geometry of the finite element model. 12
Figure 2 Water profile cases stablished in the model. 13
Figure 3 Frequency resultant values of the dynamic analysis. 16
Figure 5 Acceleration records measured in Pedernales/Ecuador during the Earthquake of 2016. 17
Figure 4 Response spectrum in acceleration for the earthquake measured. 18

INTRODUCTION

Rammed earth (RE) has been a well-known construction material throughout history (Sanchis, 2009). For example, RE was the principal material used by ancient civilizations to construct cities, forts, and monuments (Sanchis, 2009). Rammed earth shows low environmental effects and high sustainability. Consequently, the interest in RE as a construction material has grown recently (Bestraten et al, 2011). In the last two decades, several studies about RE have been developed, but there are not many investigations about the seismic performance of RE structures (Bui et al, 2016). However, research conducted by Morris & Walker (2001) has shown that these constructions have an acceptable performance during tectonic events. Therefore, it is important to assess the dynamic performance of these types of structures.

To study the behavior of RE structures during seismic events, numerical models need to be used. These numerical models are based on the mechanical properties of compacted soils. According to investigations (Villacreces et al, 2020), the mechanical properties of soil change as a function of water content. In this investigation, the shear modulus was measured at different water contents. Therefore, the water content distribution of RE structure is related to the mechanical properties of the constituent material, and the general behavior of the structure.

The seismic behavior (i. e., natural frequencies, and modal shapes) of RE buildings depends on the mechanical properties of the compacted materials (Bui et al, 2016). The degree of saturation changes the meniscus inside the soil skeleton, generating a negative pore water pressure. These negative pressures modify the elastic properties of the compacted material and, change the performance of the complete structure.

This investigation assesses the influence of water content profile on the general performance of RE structures. This research evaluated 30 cm thick rammed earth walls with different water content spatial distributions. The material properties were obtained from the research conducted by Villacreces et al (2020). These properties were assigned according to the analyzed water content profile. Finally, the modal shapes were computed to study the relationship between the wall water profile and the natural frequencies. The mechanical performance of rammed earth was computed using a free graphical interface and a finite element software (i.e., OpenSees, and OpenSeesNavigator).

Materials

This research uses the results of the investigation conducted by Villacreces et al,(2020). In this investigation, the mechanical properties of compacted kaolin were determined. The soil was a fine-grained material with Atterberg limits of 87%, 31%, and 56% for liquid limit, plastic limit, and plasticity index respectively. The soil was classified according to the Unified Soil Classification System (USCS) as a high plasticity clay (CH). Moreover, based on the Standard Proctor Test results, the optimum water content is 31% and the maximum soil dry density is 1.35g/cm3 (Villacreces et al, 2020).

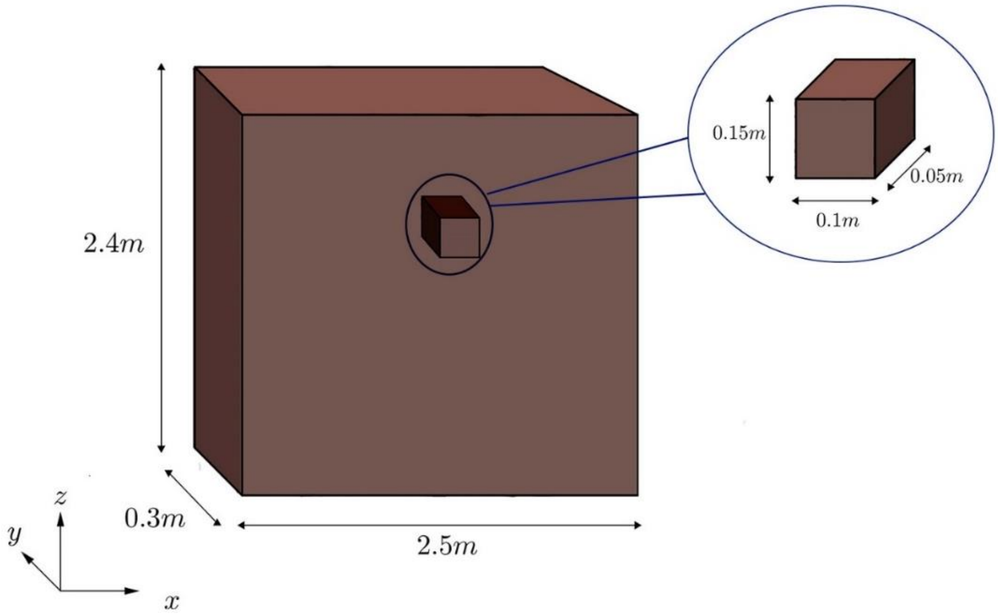

Figure 1. Geometry of the finite element model.

Using these properties, different numerical finite element models were developed to analyze the influence of water content on the dynamic performance of the structure. The modeled rammed earth wall was 2.5*m* x 0.3*m* x 2.4*m* fixed at the base. This structure was discretized in 2400 elements of 0.1*m* x 0.05*m* x 0.15*m* (Figure1). The water content profiles of the modeled structures are presented in Figure 2. The shear modulus and bulk density change according to the water profiles.

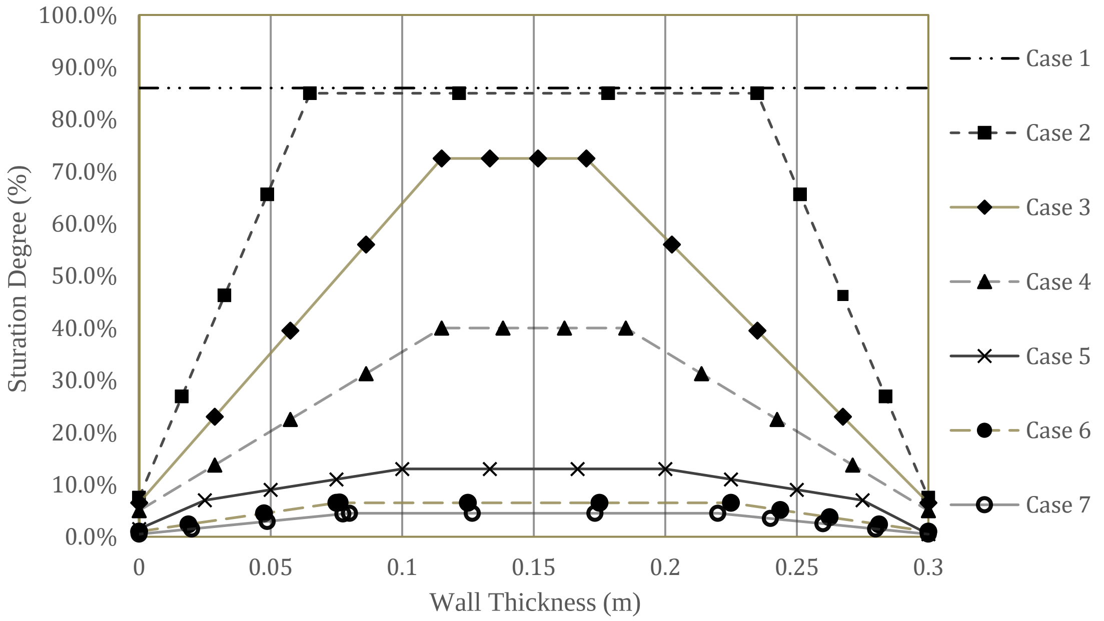

Figure 2 Water profile cases stablished in the model.

Methods:

Seven finite element models were drawn in OpenSeesNavigator. Then, these models were compiled in OpenSees. The walls were divided into six layers of 5cm along the Y direction (Figure 1). Each layer had different water content, thus different mechanical properties. The shear modulus, bulk density, and bulk modulus were assigned to each layer according to the water profile. Finally, the natural frequencies and the modal shapes for the first three fundamental vibration modes were computed.

The selected profiles show the evolution of the water content in the structure (Figure 2). This figure reflects the variation of the water profile from the beginning of the construction to the stage where the wall reaches the residual water content. The average water content was computed using the min and max values of the saturation degree in each layer as it is shown in figure 2. Equation 1 was used to compute these average values, where ($S_{r_{max}}$) and ($S_{r_{min}}$) represent the *max* and *min* saturation values respectively, and (Δx) is the 5cm thickness of each layer.

$$\bar{S_r} = (S_{r_{max}} + S_{r_{min}}) \times \frac{\Delta x}{2} \tag{1}$$

Once the saturation degree was computed in each layer, the values of shear modulus and bulk density were assigned using the results obtained from the research conducted by Villacreces et al (2020). The values of Poisson's ratio were obtained from the investigation conducted by Oh, W & Vanapalli, S (2011). Finally, the bulk modulus (*K*) was computed for each layer using equation 2. In this equation, (*Gr*) and (*v*) are the shear modulus and the Poisson's ratio respectively. In the finite element model, these properties were assigned in the material model *Pressure Independ Multi Yield.*

$$K = \frac{2G_r(1+v)}{3(1-2v)} \tag{2}$$

Table 1 shows the values assigned in the finite element model for Case 4. The wall was discretized into six layers of 5cm each and these values were assigned on each layer. The table presents the saturation degree *(S_r)*, the Poisson's ratio (μ), the bulk density (γ_{bulk}), the shear modulus (G_r), and the bulk modulus (K) calculated for each layer of the mentioned case. Once the material properties were assigned, the models were used to compute the natural frequencies and the modal shapes of the first three vibration modes.

Table 1
Properties of each layer for Case 4.

Layer	*Location (cm)*	S_r (%)	μ (%)	γ_{bulk} $\left(\frac{Kn}{m^3}\right)$	G_r (KPa)	K (KPa)
Layer 1	0-5	12.2%	17%	14.00	6.7E+05	7.9E+05
Layer 2	5-10	29.1%	20%	14.84	5.6E+05	7.4E+05
Layer 3	10-15	38.6%	20%	15.31	4.8E+05	6.4E+05
Layer 4	15-20	38.6%	20%	15.31	4.8E+05	6.4E+05
Layer 5	20-25	29.1%	20%	14.84	5.6E+05	7.4E+05
Layer 6	25-30	12.2%	17%	14.00	6.7E+05	7.9E+05

Results:

The influence of water content profile in the dynamic performance of the structure was evaluated using a finite element approach. The frequencies and vibration modes were calculated using OpenSees, and the modal shapes of all the profiles were consistent. Therefore, the first vibration mode was translational along the X-axis. The second vibration mode was torsional in the Z-axis, and the third mode was translational in the Y-axis. In the finite element model, the Y direction of the wall is the strongest axis in terms of rigidity. Rammed earth wall structures are restrained along the weak direction by the roof system. Therefore, it is reasonable to assume that the structure is going to work in the Y direction.

Figure 3 shows the results obtained in the finite element simulation, where the three vibration modes were computed. The three curves are the computed frequencies of each vibration mode. In these curves, it can be affirmed that the frequencies of the vibration increase as the water profile decrease. Additionally, in the last part of the three curves, there is an asymptote. The asymptote is reached as the water content in the structure approaches the residual state. These marked different behaviors change the dynamic response of the structure during a seismic event as a function of the water profile.

As an example, for case 1 that simulates a saturation degree of 85%, the resultant frequency in the third mode was 23.2 Hz. In comparison, the resultant frequency for case 7, which simulates a saturation degree of 4%, resulted in 49.2Hz. This example shows that the frequency for the third mode increases by 112%. This fact reflects the change in the structure stiffness as a conscience of a climatic effect. Thus, the analyzed rammed earth wall behaves differently for the same seismic event depending on the saturation degree.

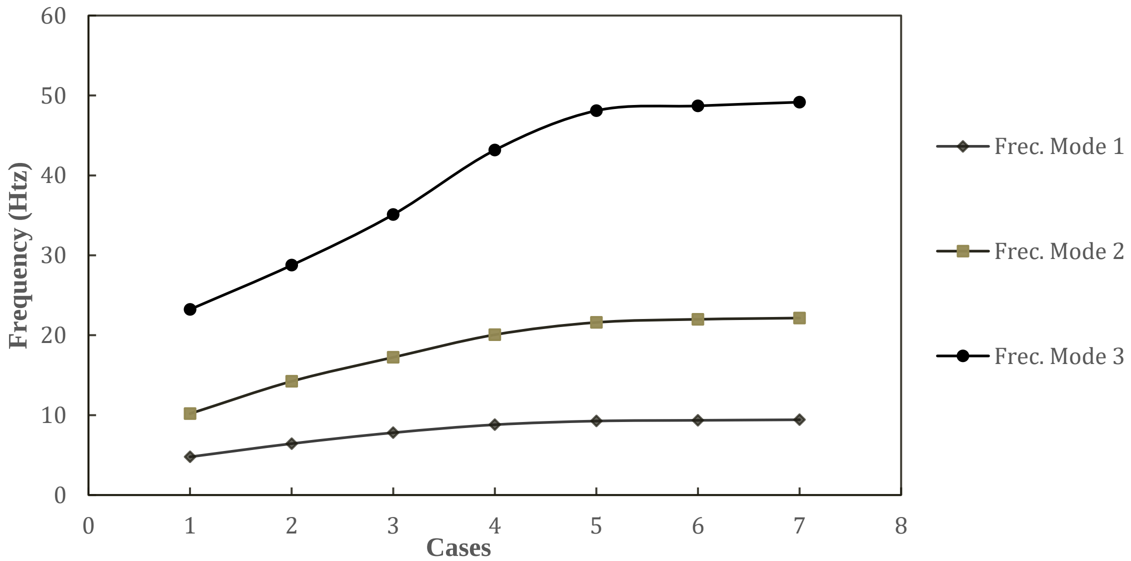

Figure 3 Frequency resultant values of the dynamic analysis.

The influence of the water content in the dynamic performance of the structure was studied using a seismic signal, and the spectral acceleration for Case 1 and Case 2 were computed. The compute accelerations are the expected value for the dry and wet water content profile during a seismic event (Figure 4). The acceleration records were measured in the city of Pedernales located in Ecuador and were obtained from the *Instituto Geofísico de la Escuela Politécnica Nacional* (Singaucho et al, 2016). This seismic signal is plotted in figure 5 and the values of acceleration are normalized by the gravitational acceleration (*g*). Therefore, the response spectrum of the seismic signal was computed using 5% damping in the elastic domain (Villacreses et. al, 2020).

The frequency of the third vibration mode was 23.2Htz for the wet state (Case 1). Consequently, the period of vibration was 0.04 seconds. In figure 4, following the first dotted line, it can be observed that the spectral acceleration for this period is 1.13g. Thus, the frequency for the residual water content (Case 7) was 49.16Hz. This frequency corresponds to a period of 0.02 seconds. Likewise, in figure 4 and following the second dotted line, the spectral acceleration for this case 0.83g. As a general comment, the spectral acceleration for this seismic signal increases by 40% between the wet and the dry state of the wall.

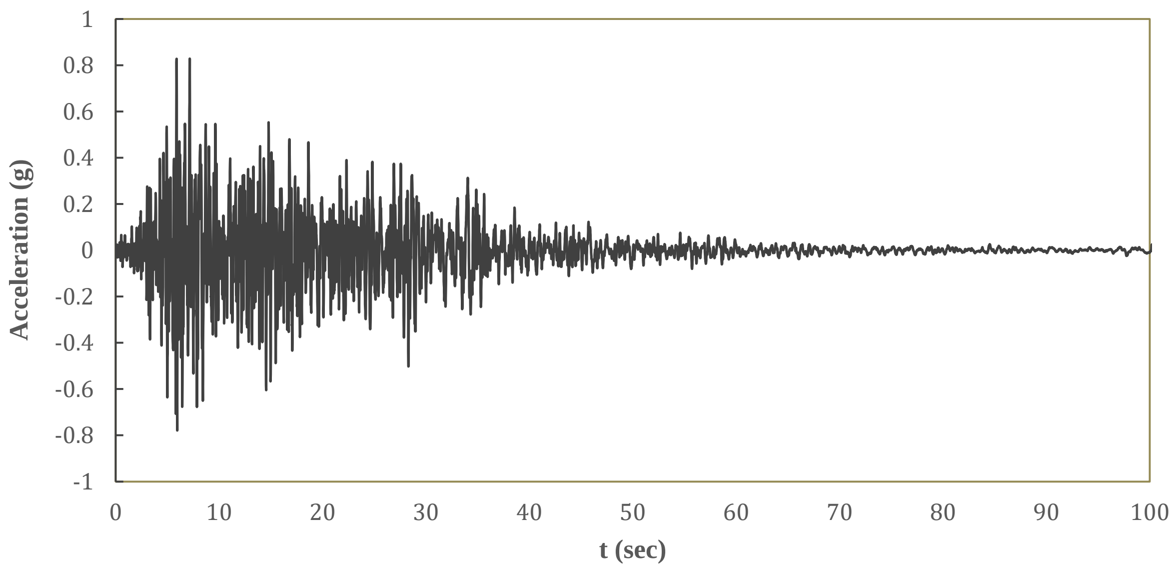

Figure 4 Acceleration records measured in Pedernales/Ecuador during the Earthquake of 2016.

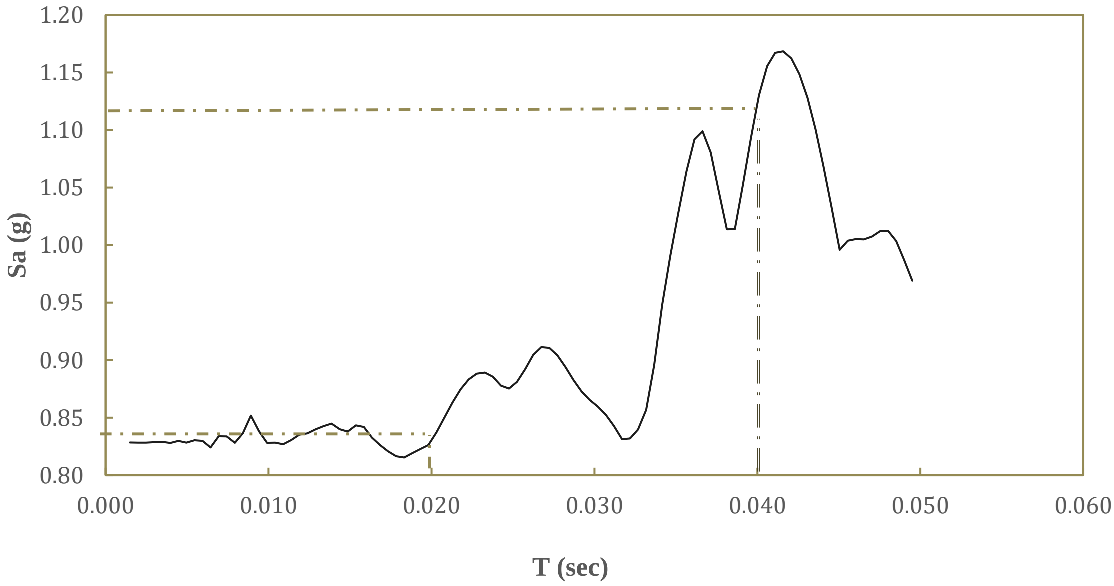

Figure 5 Response spectrum in acceleration for the earthquake measured.

CONCLUSIONS

The dynamic performance of rammed earth structures is a function of the water content profile. The frequency of vibration of RE structures increases as the water profiles approaches the residual water content. This phenomenon increases the seismic equivalent static force as the wall approaches the dry state. Additionally, the seismic design conditions could change during the service life of the structure because of the evolution of the water profile. Therefore, it is important to extend this research to predict the water content profile through computational models.

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