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A Study of the Influence of Water Content Profile on the Dynamic Behavior of Rammed Earth Structures

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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 hypothetical moisture 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 structural stiffness. Then, a response spectrum of accelerations was used to analyze the difference in the dynamic response of the structure due to the water content profile. The results suggest that the walls have different seismic behavior at the beginning of the construction phase and change with the different residual water content states of the structure.

Keywords**:** Rammed earth structures, suction, climate effect, water content profile, dynamic performance.

1. Introduction

Rammed earth (RE) has been a well-known construction material throughout history [1]. For example, RE was the principal material used by ancient civilizations to construct cities, forts, and monuments [1]. Rammed earth shows low environmental effects and high sustainability. Consequently, the interest in RE as a construction material has grown recently in some countries [2]. 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 [3]. However, research conducted by Morris & Walker has shown that these constructions have an acceptable performance during tectonic events [4]. 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 shall be based on the mechanical properties of compacted soils. According to investigations [5], the mechanical properties of soil change as a function of water content. In this investigation, shear modules were 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 material [3]. The degree of saturation changes the meniscus inside the soil skeleton, consequently the pressure of water that surrounds the soil particles also changes. Lower saturation means a negative pore water pressure, modifying elastic properties of the compacted material and changing the complete structural performance.

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 seven different water content spatial distributions (called “cases” in this research). The material properties were obtained from the research conducted by Villacreces et. al [5]. 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 the rammed earth wall was computed using a free graphical interface and a finite element software (i.e., OpenSees, and OpenSeesNavigator).

2. Materials

This research uses the results of the investigation conducted by Villacreces et. al [5], where 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. It was classified according to the Unified Soil Classification System (USCS) as a high plasticity clay (CH). Also, based on the Standard Proctor Test results, the optimum water content was 31% and the maximum soil dry density was 1.35g/cm3 [5].

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 2.5m x 0.3m x 2.4m, fixed at the base. This structure was discretized in 2400 elements of 0.1m x 0.05m x 0.15m (Figure1). Water content profiles of the modeled structures are presented in Figure 2. These profiles were selected based on the research conducted by [6]. Shear modulus and bulk density change according to the water profiles, and their values are obtained from [5].

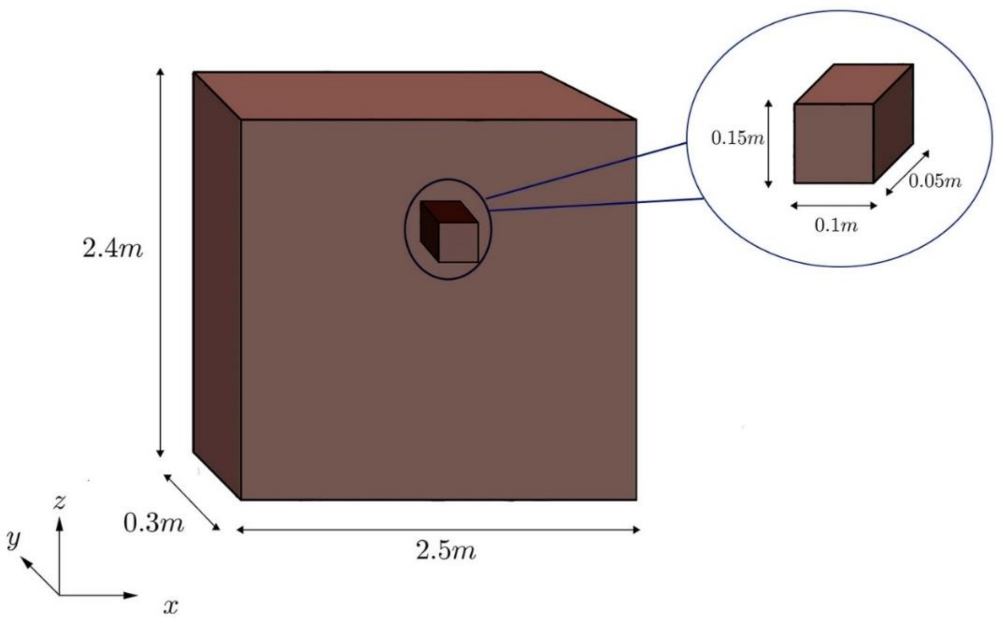

Fig. 1 Geometry of the rammed-earth wall finite element model

3. Methodology

Seven finite element models were drawn in OpenSeesNavigator and compiled in OpenSees. Walls were divided into six layers of 5cm-thick along the Y direction (Figure 1). Each layer had different water content, thus different mechanical properties. Shear modulus, bulk density, and bulk modulus were assigned to each layer according to the water profile and each finite element model represents each of the seven water profile cases considered. 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.

$$\overline{S_r} = (S_{r_{max}} + S_{r_{min}}) \times \frac{\Delta_y}{2} \tag{1}$$

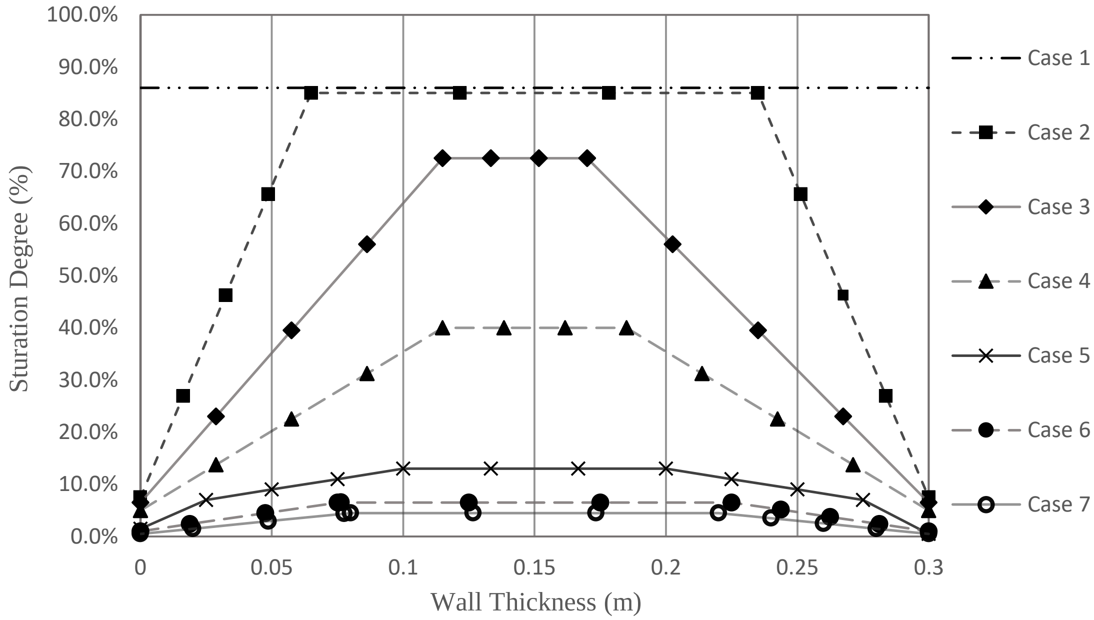

Fig. 2 Water profile cases considered for the seven finite element models.

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 [5]. Poisson's ratio values were obtained from the investigation conducted by Oh & Vanapalli [7]. Finally, the bulk modulus (K) was computed for each layer using Equation 2, where (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 inside OpenSees (?).

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

As an example, Table 1 shows the different values assigned in the finite element model for the water profile case 4. The wall was discretized into six layers (5cm-thick) and the mentioned values were assigned to each layer. Table 1 presents the saturation degree (S_r), Poisson's ratio (μ), bulk density (γ_{bulk}), shear modulus (G_r), and 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.

4. 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. The first vibration mode was translational along the Y-axis. The second vibration mode was torsional on the Z-axis, and the third mode was translational on the X-axis. In the finite element model, the X 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 X-direction.

Table 1: Final properties for each layer according to the water profile case 4.

Layer	*Location (cm)*	S_r (%)	μ (%)	$\gamma_{bulk}\left(\frac{Kn}{m^3}\right)$	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

Figure 3 shows the three main vibration frequencies obtained in the finite element simulations of all the analyzed cases. As it is possible to observe, frequencies increase as the water profile decrease. Additionally, in the last part of the three curves corresponding to the lower saturation degree cases (lower than 10%), there is an asymptote, showing stability for those water contents. The asymptote is reached as the water content in the structure approaches the residual water content. These marked different behaviors change the dynamic response of the structure during a seismic event as a function of the water profile.

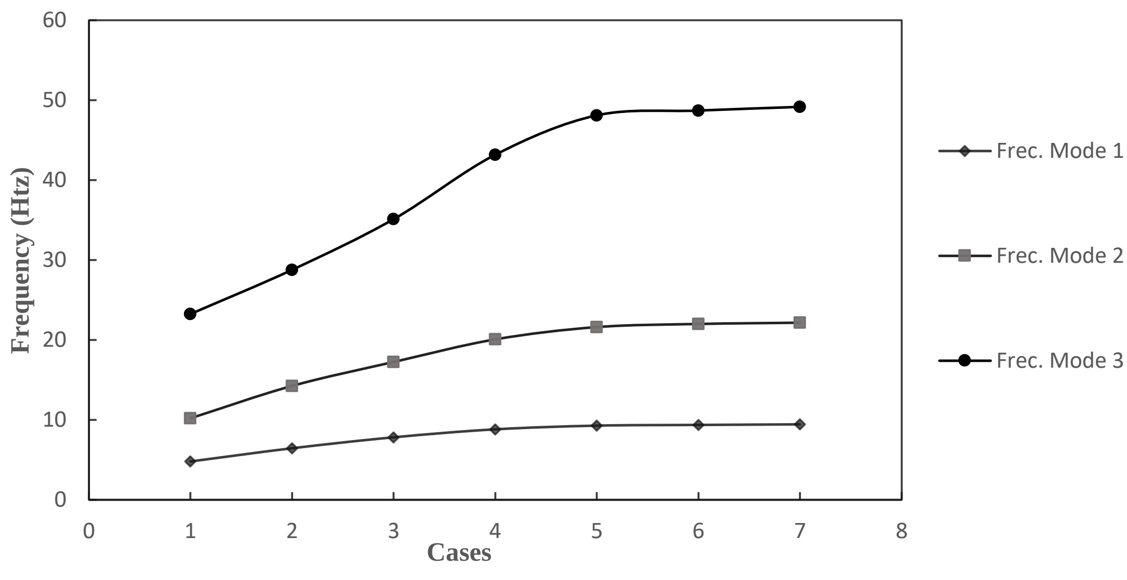

Fig. 3 Resultant values of the three main frequencies for the dynamic analysis of all cases.

As an example, for case 1 that simulates a saturation degree of 85%, the resultant frequency in the third mode was 23.2 Hz, while for case 7 (simulating a saturation degree of 4%), such frequency was 49.2Hz, that is 112% higher. This fact reflects the change in the structural stiffness as a conscience of a climatic effect. Thus, the analyzed rammed earth walls behave differently for the same seismic event depending on the saturation degree.

The influence of the water content in the dynamic performance of the structure was studied using the strong motion record of the Pedernales-Ecuador earthquake – April 2016 [8] and its elastic acceleration spectrum (5% damped) (Figures 4 & 5). The spectral accelerations for the third vibration mode periods of Case 1 (wet) and Case 7 (dry) models are shown in Figure 5. It is possible to observe that frequency of the wet state (Case 1) was 23.2Hz (period T=0.04s), corresponding to a spectral acceleration of 1.13g, while for the dry state (Case 7), the frequency was 49.16Hz (period T=0.02s), corresponding to 0.83g. Therefore, the spectral acceleration for the wet state is 36% higher than the dry state of the wall, for this particular earthquake record.

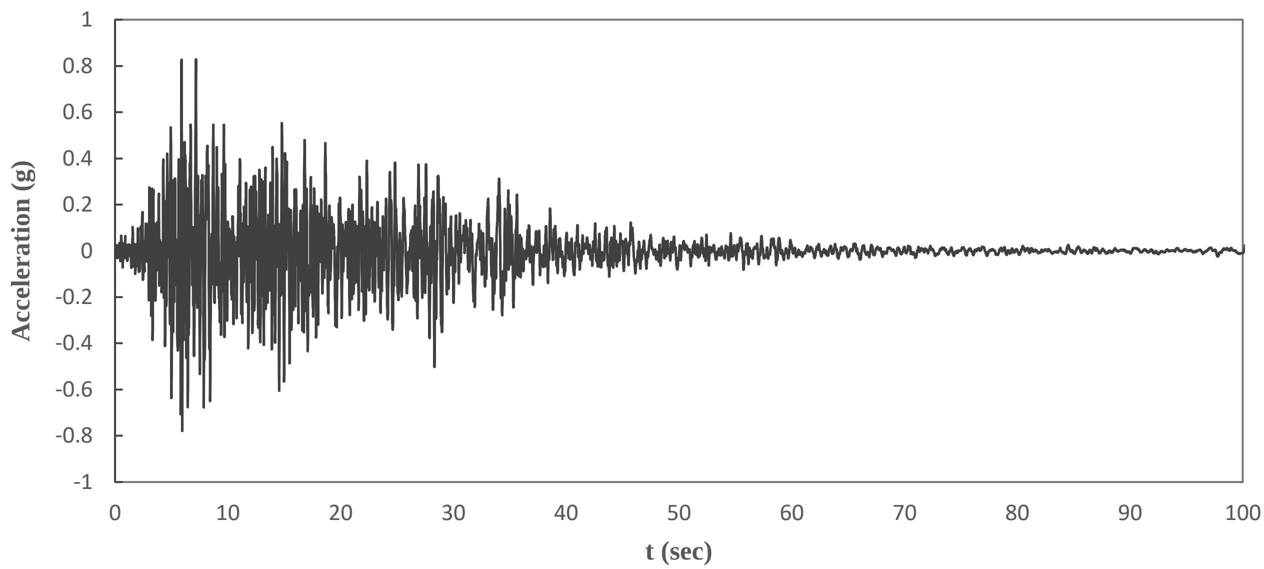

Fig. 4 Acceleration record of Pedernales-Ecuador earthquake, April 2016 (source: IG-EPN).

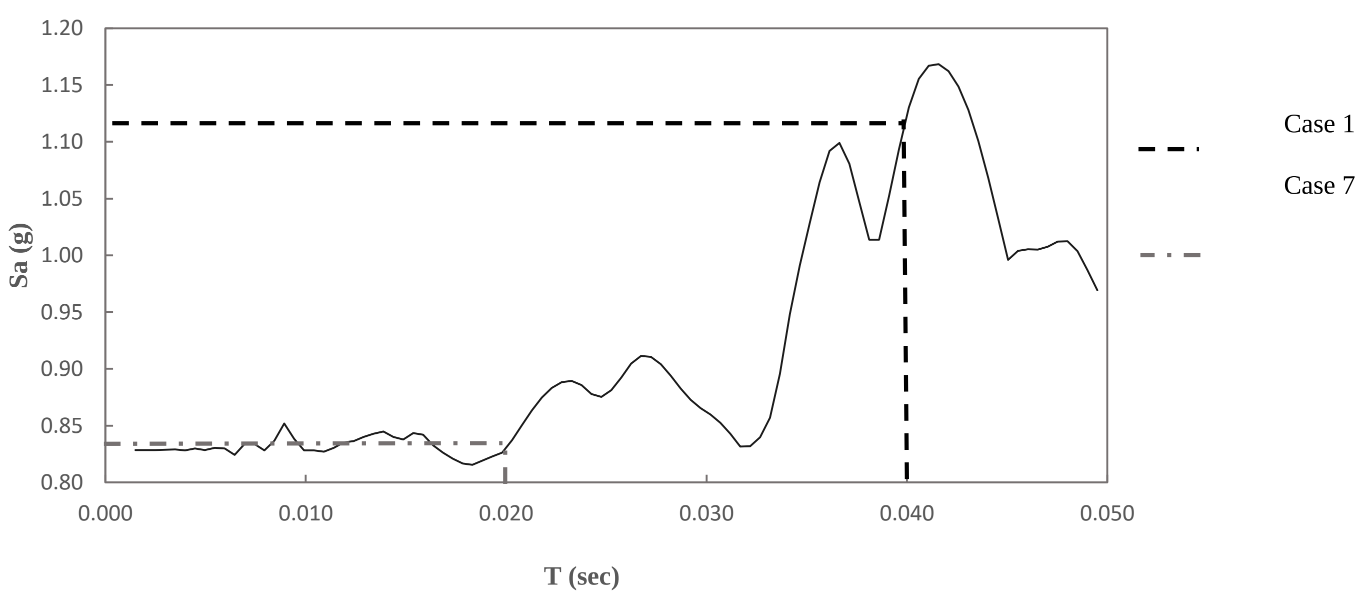

Fig. 5 Acceleration response spectrum (5% damped) of the Pedernales-Ecuador earthquake, April 2016 and spectral values for the third vibration mode, Cases 1 (wet) and 7 (dry) finite element models.

5. Conclusions

The dynamic performance of rammed earth structures depends on the water profile within them. As shown in this research, vibration frequencies of RE structures have a reverse behavior according to the saturation degree. Rammed earth structures are stiffer when the water profile inside is lower, and vice versa, changing dynamic properties and the overall expected seismic performance. Depending on the amplitude and frequency content of the earthquake, rammed earth structures could suffer very different seismic demands according to their water content. Also, water content conditions along the service life of the structures will change, therefore, dynamic properties and expected seismic behavior will also change in time. Therefore, a method to predict the quantity and distribution of water profiles inside rammed earth structures could be very important for the seismic design of new RE structures and seismic evaluation of existing RE structures.

6. References

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