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Seismic Behavior of Rammed Earth Walls under Saturated and Dry Conditions

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Abstract **-** This research studies the seismic response of rammed earth walls under extreme water content conditions: fully saturated and completely dry. Using numerical simulations in OpenSeesPy, three seismic records with distinct frequency content—Loma Prieta, Chi-Chi, and Landers—were applied to a compacted earth wall model. Results reveal significant variations in acceleration, displacement, and frequency response between wet and dry conditions, highlighting the critical impact of water content on dynamic properties. This analysis extends prior research by incorporating diverse seismic records, enhancing the understanding of material behavior under varying environmental conditions.

Keywords: Rammed Earth, seismic simulation, OpenSeesPy, dynamic properties, sustainability.

1. Introduction

Rammed Earth Walls (REW) are sustainable construction materials that have been widely used due to their low carbon footprint, availability and affordability [1-3]. This traditional technique involves compacting layers of moist fine soils within a formwork. Since REW are commonly used outdoors, they are exposed to varying saturation levels, ranging from fully saturated to partially saturated or completely dry state. Therefore, their seismic performance remains a critical concern, as moisture fluctuations significantly affect soil mechanical properties [3,4].

In a soil structure, saturation level affects soil strength by modifying water pressure, its stress state and elastic properties [1]. Consequently, as mechanical properties of the soil change with water content, so do its dynamic response. Villacreses et al. [1] examined the seismic response of REW under saturated and dry states, revealing higher accelerations in wet conditions. Soil samples with low suction exhibit soft behavior under seismic loads, whereas those with high suction demonstrate a stiffer response and greater resistance [5,6]. Mechanical properties, particularly cohesion, decrease with saturation, which may compromise structural integrity during seismic events [6,7].

This research employs a numerical simulation in OpenseesPy to analyze seismic behavior of a REW under extreme water content, completely saturated and completely dry. This REW was then subjected to three different seismic signals, from Loma Prieta, Chi-Chi and Landers earthquakes. Finally, acceleration, displacements and frequency content are going to be compared. Understanding how internal water content affect the dynamic response of REW is very important for a safer design in seismically active regions, like Ecuador. [6] analyze how moisture gradients influence the cohesion and friction angle of REW, identifying suction as a key factor that enhances resistance to drying. This effect could also be considered in structural modeling as further work.

2. Materials and Methods

This section is divided into two parts. In the material subsection there are going to be explained soil mechanical properties taken as inputs for the REW simulation. These properties are based on data taken from [1] experimental modeling. The methods subsection describes the model discretization and seismic records used.

2.1. Materials

This research uses experimental data taken from [1], where a scaled rammed earth wall was built up in a laboratory and its dynamic response was analyzed in a dynamic shear rheometer. Villacreses et al. use high plasticity clay (CH), with a liquid limit (LL) of 87%, a plasticity index (PI) of 50%, a maximum dry density (ρ_d) of 1.34 g/cm^3 and an optimum water content (w) of 31.40 % according to a Standard Proctor Essay [1]. Soil mechanical properties for the modeling process are shown in table 1.

Table 1: Soil properties used in the modeling.

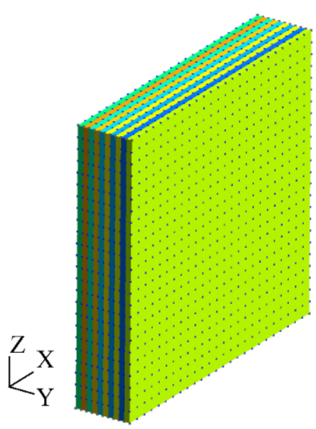
Parameter	Value
LL [%]	87.00
$\boldsymbol{PI}$ **[%]**	50.00
$\boldsymbol{\rho_d}$ **[g/cm^3]**	1.34
$\boldsymbol{w}$ **[%]**	31.40

Material dynamic properties, such as the modulus of elasticity and shear modulus, were adjusted for extreme wet and dry conditions based on experimental data, where material suction, maximum shear modulus, bulk density and extended failure envelope of the shear plane were related [1].

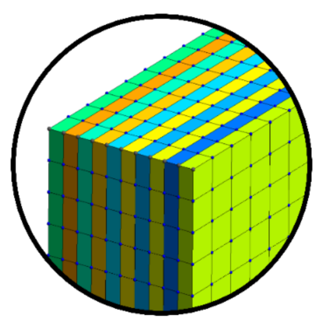
2.2. Methods

2.2.1. Rammed earth wall model

This study generates a 2.4-meter-high, 2.5-meter-long and 0.5-meter-thick REW. To create the FEM of the wall, GMSH software was used. The wall was discretized in the x and z-direction with a constant value of 10 cm. The y-direction was divided into 10 sections, each one of 5 cm, due to the interest in further investigation in the analysis of gradient saturation conditions along its width. Figure 1.a shows the discretization of the REW, and figure 1.b shows the mesh detail in each direction.



a)



b)

Figure 1: (a) Rammed earth wall FEM model in GMSH and (b) detail of the wall discretization.

2.2.2. Seismic Records

Three seismic records were selected to analyze the wall's response under varying frequency content: Loma Prieta (1989), predominantly low-frequency content; Chi-Chi (1999), mixed-frequency content; and Landers (1992), high-frequency content. Each record was processed to remove noise and applied in the x-direction. The seismic signal was applied to the bottom of the wall, and the results were taken at the top.

3. Results and Discussion

3.1. Acceleration and displacement

Figure 2.a illustrates the maximum acceleration response of the REW under saturated and dry conditions for the Loma Loma Prieta, Chi-Chi, and Landers earthquakes. Results show a considerably higher peak acceleration in the wet conditions conditions across all seismic records. Figure 2.b shows the maximum displacements. There is a significant increase in displacement for the completely saturated condition across all records. The largest difference in the maximum acceleration and displacement is observed under the Landers earthquake, the one with the highest frequency content.

Therefore, water content significantly reduces the structure's stiffness, leading to higher deformations under seismic loading. These findings align with theoretical expectations, as saturated soils have reduced stiffness and increased deformation potential [1,3].

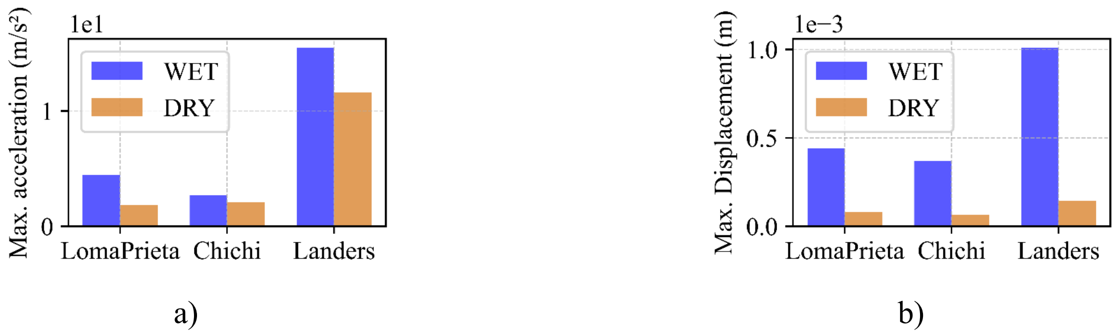


Figure 2: (a) Peak acceleration and (b) displacement comparisons between wet and dry conditions.

3.2. Frequency Analysis

Figure 3 shows the comparison between the FFT obtained for Loma Prieta, Chi-Chi and Landers records for the two water contents analyzed. All three records show a peak in the frequential content in approximately 22.5 Hz and 40.0 Hz for the saturated and dry conditions respectively.

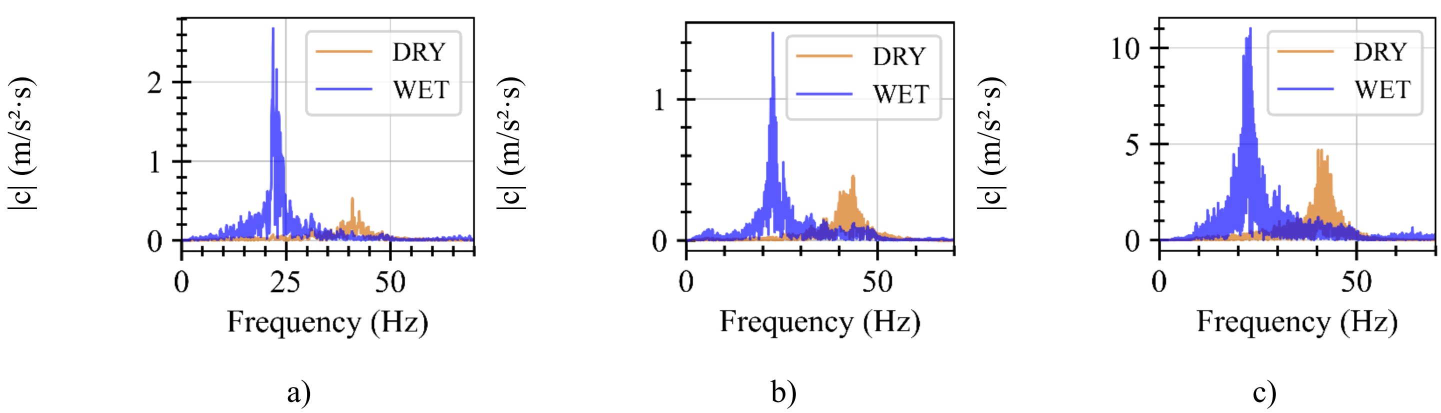


Figure 3: Comparison of FFT between wet and dry conditions for records a) Loma Prieta, b) Chi-Chi and c) Landers.

Results evidence different frequency peaks for saturated and dry conditions. Saturated walls show dominant frequencies closer to seismic input spectra, while dry walls showed higher frequencies due to increased stiffness. Results show a marked shift in spectral amplitude and dominant frequency due to water content variation.

3.3. Comparative Performance Across Records

The Landers earthquake, with high-frequency content, induced the smallest differences between wet and dry suggesting reduced sensitivity to water content at higher frequencies. In contrast, the Chi-Chi earthquake revealed differences, while Loma Prieta highlighted the most pronounced variations.

4. Conclusion

This study confirms that water content has a significant impact on the seismic response of REW. Simulations under fully saturated and completely dry conditions, using seismic records from Loma Prieta, Chi-Chi, and Landers, indicate that saturation amplifies peak accelerations and displacements, especially under high-frequency records. The greatest difference in maximum acceleration and displacement occurs during the Landers earthquake. Additionally, dry conditions exhibited higher dynamic stiffness and higher dominant frequencies. The wet condition evidence a pronounced peak around 22.5 Hz, suggesting a lower stiffness, whereas the dry condition shows a more distributed frequency response with lower amplitudes. These findings highlight the importance of considering water content in the design and analysis of rammed earth structures, particularly in seismic-prone regions, and validate the proposed model for analyzing dynamic behavior across various scenarios.

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