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INFLUENCE OF THICKNESS OF AN UNSATURATED SOIL DEPOSIT ON DYNAMIC RESPONSE OF A STRONG EARTHQUAKE

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ABSTRACT

The dynamic response of soil is fundamental in the seismic design of structures and in solutions to vibration and stability problems, amongst many other applications. The partial saturation condition and the capillary forces have been recognized recently as fundamental features that control the spectral response of a site. Nonetheless, the relation amongst the partial saturation condition, the thickness of the unsaturated materials from a site and the accelerations history of the earthquakes in the spectral parameters on surface have been relatively little studied and understood. Those relations are important in tropical environments located near the equator, with diverse thickness of unsaturated soils and different geologic provenance beneath densely populated areas. In this work, an analysis of the spectral acceleration variation is presented considering different thicknesses of an unsaturated soil profile for a strong earthquake. Additionally, the impact of the partial saturation condition of the materials is studied using an elastic one-dimensional simulation. The obtained results show that the variability of soil deposit thickness induces relevant changes in the dynamic response. This changes are additional to those associated with the matric suction effect in the materials response, such as the increase of the vibration fundamental frequency and the decrease on the energy dissipation in the profile. Furthermore, the effect of the accelerations history on the dynamic response decreases proportionally to the increase of the deposit thickness. The outcomes present interesting trends that may well be considered in more detailed future works about seismic zonation in this kind of conditions.

Keywords: Shear Modulus, Damping Ration, Earthquake, Suction, Spectral Acceleration, Local Dynamic Response, Unsaturated Soils.

1. INTRODUCTION

The conditions of a soil deposit in a seismic event are vital when performing the analysis of its dynamic response. Within these local site conditions, the deposit saturation and its stress state can be highlighted as features that directly influence the soil dynamic properties values such as the shear wave velocities (V_s), small strain shear modulus (G) and Damping Ratio (D) (Vassallo, Mancuso, and Vinale 2007). To determine these parameters, several models have been proposed by various authors, who manage to establish equations through empiric and theoretical relations mainly based in the soil properties such as particle size, water content, plasticity index, soil porosity and void ratio, among others (Biglari and Ashayeri 2011), (Mahnoosh Biglari et al. 2011). Another way to obtain directly these dynamic parameters is through cyclic triaxial and resonant column testing, where the values of maximum shear modulus (G_{max}) and minimum damping ratio (D_{min}) are affected by the influence of confinement level, matric suction, net mean stress, and microstructure (Pineda, Colmenares, and Hoyos 2014) (Hoyos, Suescún, and Puppala 2015), (Ghayoomi, Suprunenko, and Mirshekari 2017), (Vassallo et al. 2007), (Mancuso, Vassallo, and d'Onofrio 2002) and novel experimental methods (Le and Ghayoomi 2016), (Dong and Lu 2016). In

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partially saturated soils, experimental results from different authors show that certain relationships between dynamic properties (G), (D) and (p-U_a) are strong dependent of material particle size, nonetheless, there is general tendencies that indicates that matric suction level and net confinement pressure causes that (G) is proportional to those levels and damping ratio (D) is inversely proportional (Pineda and Pete 2017).

In recent years, some studies have been carried out to evaluate the dynamic response of soil deposits under partial saturation conditions through linear and equivalent linear modelling (Biglari and Ashayeri 2013; Ghayoomi and Mirshekari 2014), and experimentally by physical models that simulates the conditions of an earthquake (Mirshekari and Ghayoomi 2017), however, none of the authors has explicitly evaluated the influence of the thickness of the soil layers on the response conditions for a given earthquake. Therefore, in this article a series of one-dimensional modeling was carried out in the EERA program (Equivalent-linear Earthquake site Response Analysis) program introducing a seismic signal of a strong earthquake according to Richter scale (Ms>6). In the simulations, in addition of the consideration of dynamic parameters affected by certain conditions of net confinement and matric suction, the variation of the thicknesses of the soil profile with the chosen earthquake was included, seeking to show how these site conditions affect the dynamic response of the soil. The analysis of the results was carried out by using the results of spectral accelerations in the response spectra (Sa), the Peak Ground Acceleration (PGA) and the F_{PGA} amplification factor.

2. DEFINITION OF PARAMETERS FOR SIMULATION

2.1 Soil Properties

For the simulations performed in this work, the results of dynamic testing obtained for a silty sand (SM classification USCS), which has been used in several investigations both in natural and compacted states to assess the influence of confinement level (p`, p-U_a), the microstructure, the magnitude of the matric suction (U_a-U_w) and the level of deformations linear dynamic properties are used Table 1, show the index properties of this material.

Table 1. Properties of the material used for the modeling.

Mat	**Gs**	**LL (%)**	**LP (%)**	**IP (%)**	**% Fines**
SM	2,71	26,0	21,0	5,00	13,13

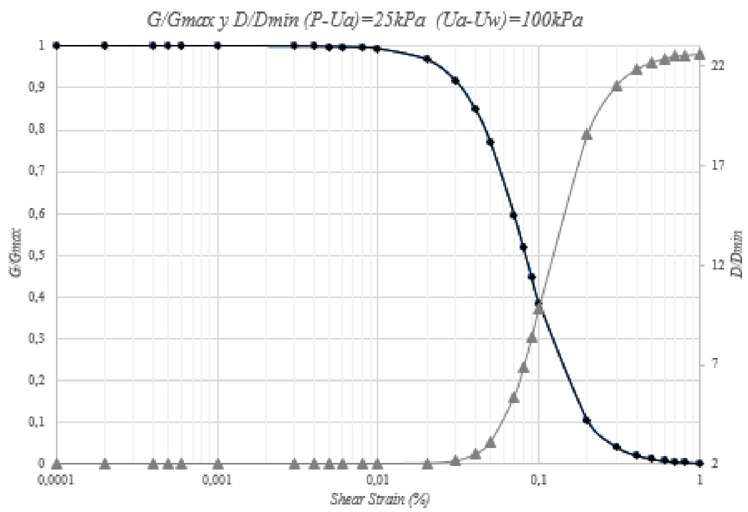
* *Properties taken from* (Hoyos et al. 2015)

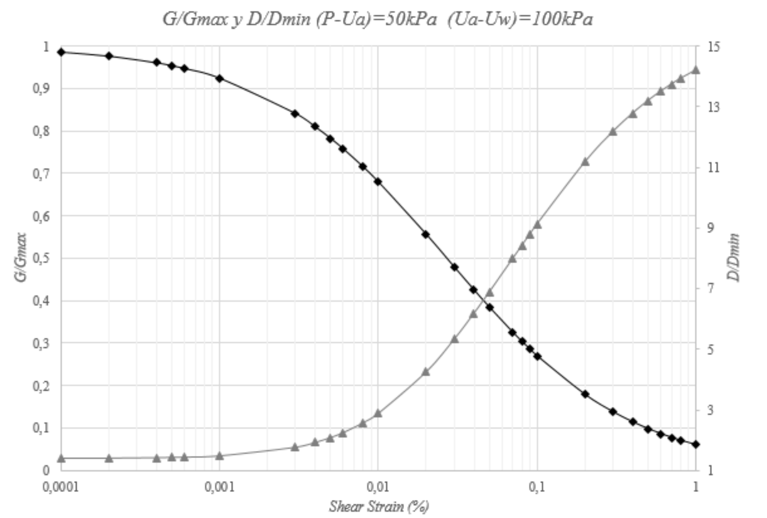
The dynamic properties used in this work are presented in figure 1, which have been adapted from the Pino (2013) compiled by Pineda and Pete (2017). In this figure, curves of G/G_{max} y $D/D_{mín}$ for matric suctions (U_a-U_w) of 25 kPa y 100 kPa and net confinement stresses (P-U_a) of 25, 50, 100 y 200 kPa are shown, obtained from RC testing with suction control through axis translation technique. Equations (1) and (2), established from the experimental points, show the suggested variations of G/G_{max} and D/D_{min}, for cyclic shear strains between 0.0001% and 1%.

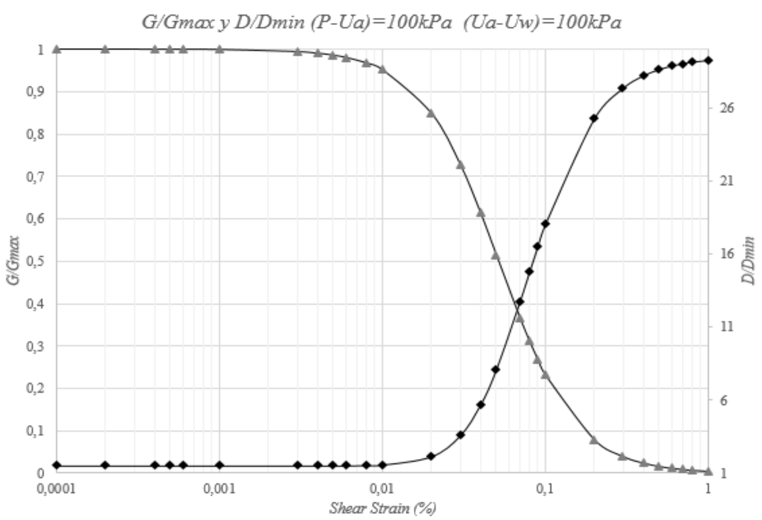
$$\frac{G}{G_{Max}} = \frac{1}{(1 + a(\gamma)^b)^c} \qquad (1)$$

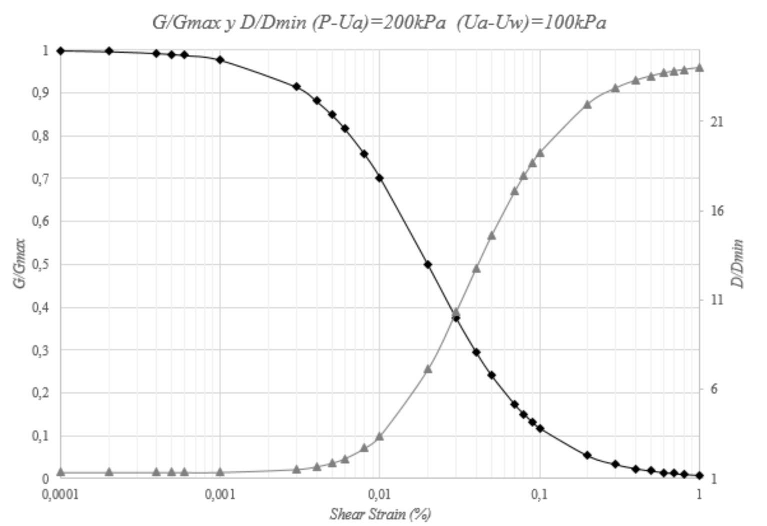
In these equations, (γ) represents the shear strain in percentage, and the factors a, b, c, x and Z are adjusting parameters that depends on confinement conditions and matric suction to which the material was subjected.

$$\frac{D}{D_{min}} = x\left(\frac{G}{G_{Max}} - 1\right)^2 + Z \qquad (2)$$









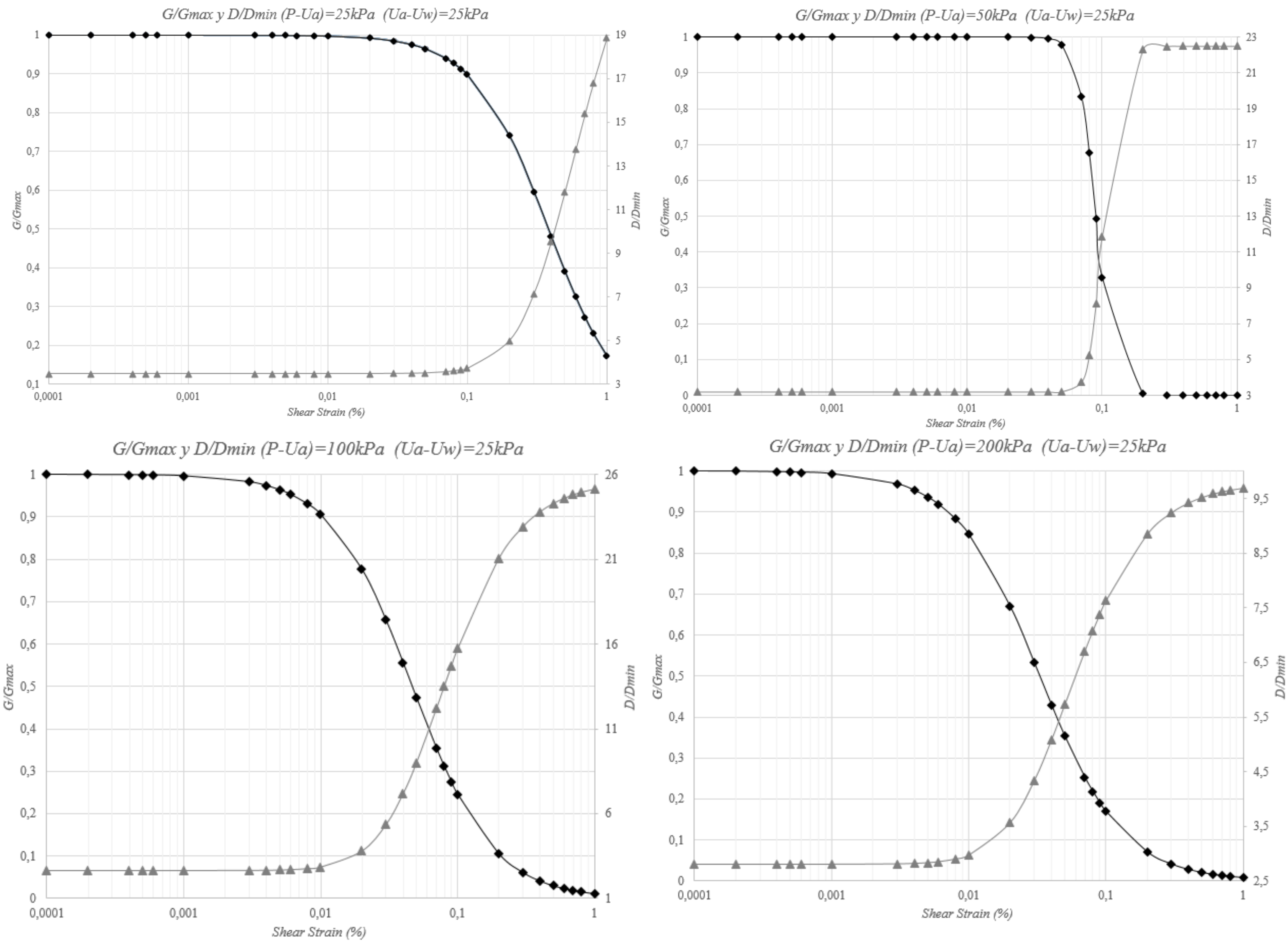


Figure 1. Graphics of G/Gmax y D/Dmin obtained by the empirical equations raised by (PINO 2013)

2.2 Discretization of the Soil Profile and Characteristics of the Earthquake

The seismic event selected in this work corresponds to the earthquake recorded by the station FKO001 on March 20, 2005 in KYUSHO-JAPON, which epicenter was located offshore in front of the city of Fukuoka, this earthquake is classified historically as one of the strongest earthquakes that have shaken the japanese region since 1923. According to the record of measured instrumental accelerations, the peak acceleration reached was 0.251 (g) (Figure 2), the earthquake had a magnitude of 7.00 on the Richter scale, and it could be considered a strong event. This earthquake has been used in some countries in South America located near the equator line, where focal mechanisms are similar to reproduce seismic response spectra of different soil deposits (FOPAE 2010). Table 2 shows the main characteristics of the movement.

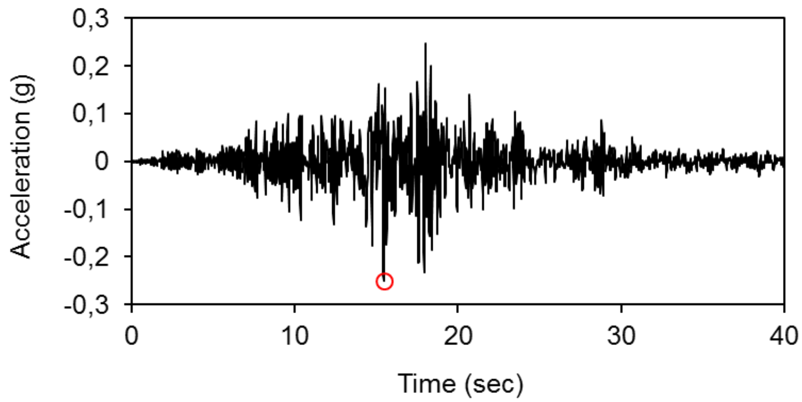


Figure 2. Accelerogram corresponding to earthquake KYUSHO-JAPON.

Table 2. Relationship of seismic signals used for the modeling.

NOMBRE SISMO	ESTACIÓN	MAGNITUD	Amax
KYUSHO-JAPON	FKO0001	7.00	0.251

*Own source

For dynamic one-dimensional simulations, four synthetic soil profiles were defined with variable thickness (H) of 6.00m, 9.00m, 12.00m and 20.00m in order to establish the influence of thickness on spectral response. In all profiles, values of constant matric suction (U_a-U_w) with depth of 25kPa and 100 kPa were considered according with the experimental values imposed in dynamic testing, and confinement level were determined by using the net vertical stress(σ_v-U_a) conserving the medium total unit weight of the samples associated to figure 1.

3. RESULTS AND DISCUSSION

As previously mentioned, dynamic response was established by EERA program, assuming that the soil as an elastic media which behavior in wave propagation is independent of pore fluid. Figures 3 and 4 show the response spectra in terms of (Sa) obtained in surface for both matric suctions. Next, analyzes in terms of Peak Ground Acceleration (PGA) and the amplification factor of accelerations F_{PGA} which corresponds to the relationship between the maximum acceleration produced in any layer with the maximum acceleration produced in the base $F_{PGA}=PGA_m/PGA_b$. Associated with dynamic response are presented.

3.1 Spectral Acceleration (Sa)

As can be seen in figures 3 and 4, a generalized tendency is evidenced in dynamic response for both constant-suction profiles, the decrease of the maximum values of (S_a) as the thickness of soil profile increases. For spectral response of profiles with constant (U_a-U_w) of 25 kPa, peaks of (S_a) are located between values of 0.38g for 6.00m thickness and 0.08g for 20.00m profile, while for (U_a-U_w) of 100kPa the values are 0.390g and 0.038g, respectively. These tendencies could be associated to the modification on dissipation energy of the system in one-dimensional propagation, which is profoundly affected by thickness of the deposits at constant suction conditions instead increases in confinement level with depth.

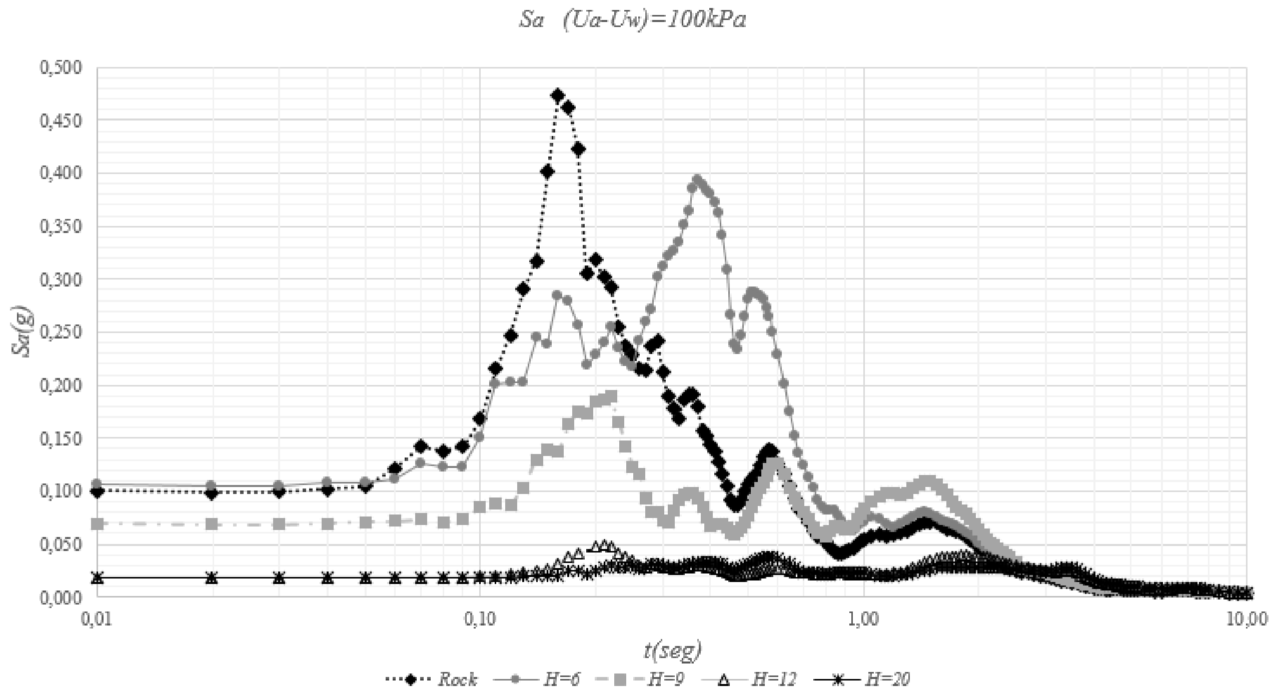


Figure 3. Acceleration spectrum obtained for a soil profile submitted to a constant matrix suction of 100kPa.

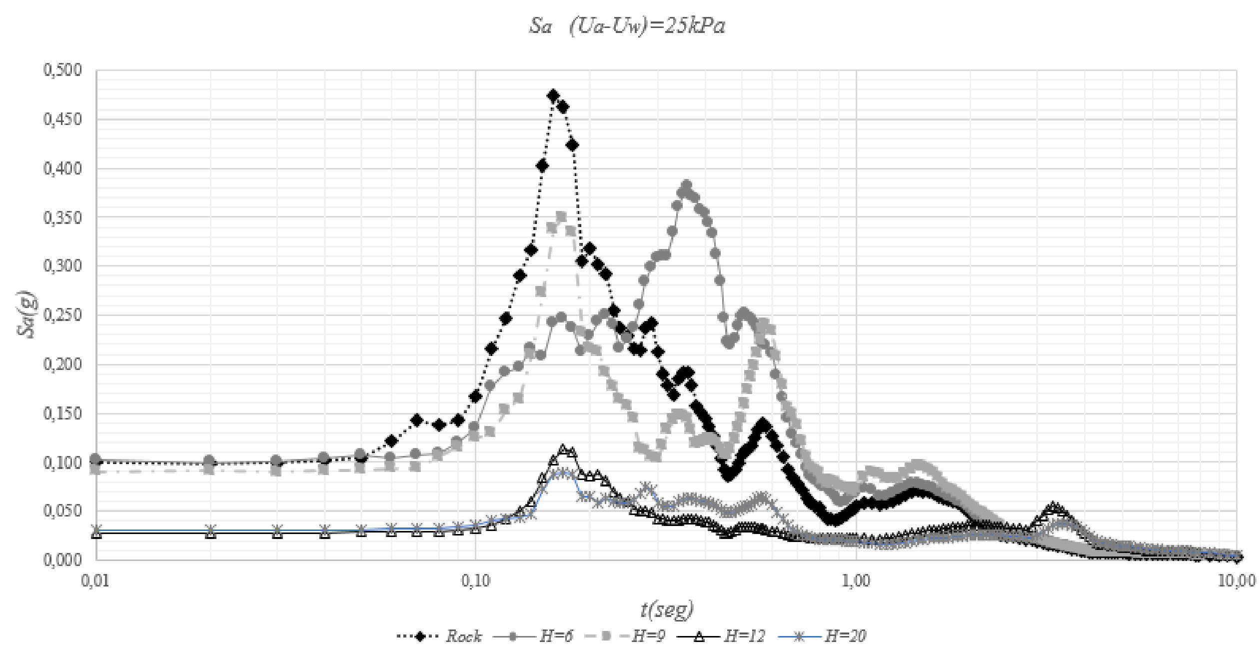


Figure 4. Acceleration spectrum obtained for a soil profile submitted to a constant matrix suction of 25kPa.

Figure 5, show the maximum values of (S_a) for profiles with constant (U_a-U_w) of 25 kPa and 100 kPa for each analysed thickness. It could be noted that for soil profiles of constant suction 100 kPa, the attenuation of accelerations is more pronounced than for profiles with 25 kPa constant suction. For low suction profiles, the maximum values of (S_a) are higher than those values of higher suction, probably because the influence of capillary forces on damping characteristics of materials and its influence in one-dimensional dynamic analysis is less pronounced for those materials.

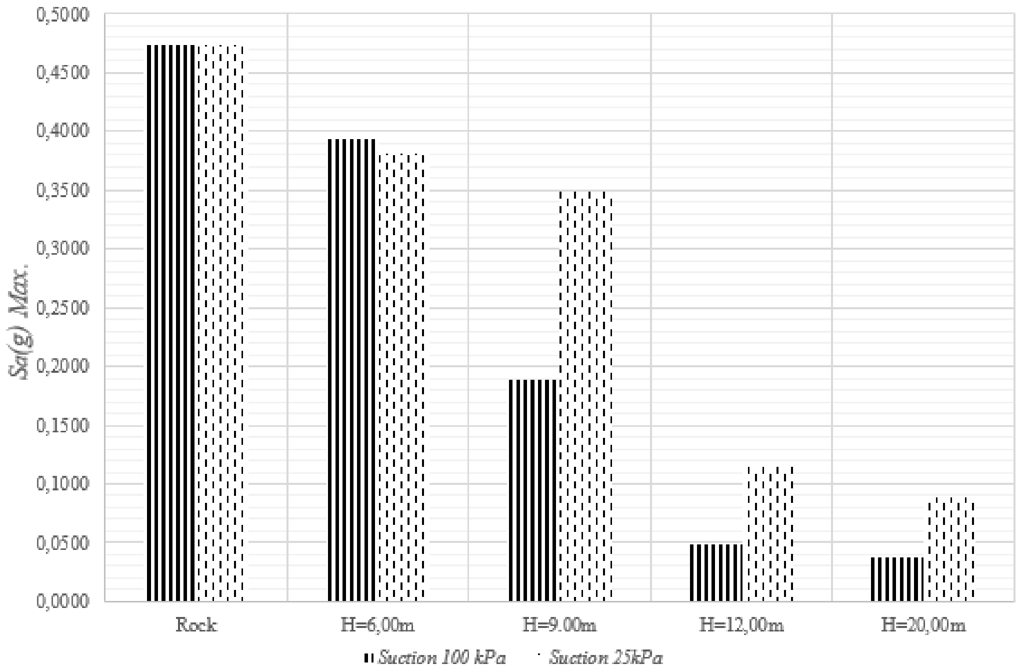


Figure 5. Variation in the dissipation of energy in each of the thicknesses in relation to the change in the matrix suction of the material.

Similarly, when analysing times predicted where the maximum spectral acceleration occurs (see figure 6), it is observed that for soil profile where (U_a-U_w = 100 kPa), peaks of (S_a) response are generated afterwards to those generated by soil profiles of (U_a-U_w = 25 kPa), however, all of them before the first second. This is possibly due by the conditions of vibration generated in the layers of each profile according to the influence of dynamic properties used in the model. The role that dynamic stiffness and damping of soil skeleton plays in wave dissipation, cyclic strains in soil layers and maximum outward accelerations in soil profiles surface is different with matric suctions and energy released in a one-dimensional scenario is higher when (U_a-U_w) decreases.

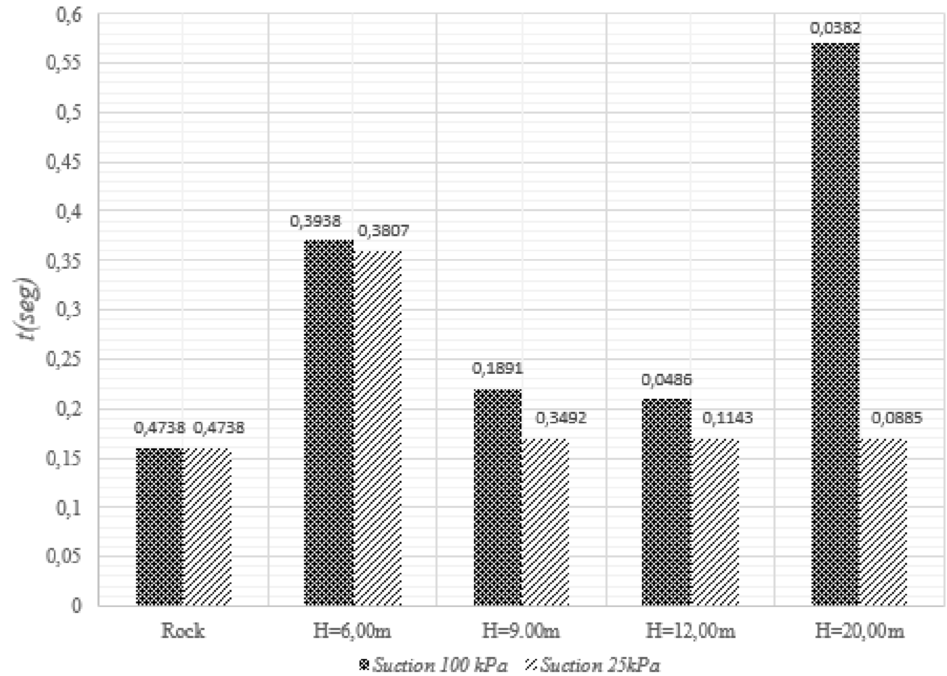


Figure 6. Instant of time in which the spectral peak acelración is generated for each of the analyzed thickness and suctions matrix established.

3.2 Peak Ground Acceleration predicted on surface (PGA) and (F_{PGA})

The PGA is one of the parameters most used to show the effects of earthquakes on the dynamic response of a soil profile, in table 3, the *PGA* values obtained for the thicknesses analysed for each constant suction are presented. It is important to note that the value in maximum acceleration in rock at the base of profiles does not vary because this magnitude depends on seismic event.

Table 3. PGA values obtained PGA each thickness according to the matrix suction used.

Thickness (m)	***Peak Ground Acceleration* PGA - (g)**		***Variation between (Ua-Uw) from 25kPa to 100 kPa (%)***
	$(U_a$-$U_w)$=100kPa	**$(U_a$-$U_w)$=25kPa**	
6	0,120	0,268	44
9	0,066	0,094	70
12	0,018	0,028	64
20	0,018	0,031	58
Rock	**0,474**	**0,474**	-

As can be seen, the increase in thickness generates an attenuation in the *PGA* value for the two conditions analysed, additionally it is evident that the decrease occurs in a more pronounce way in soil profile with matric suction of 25kPa, where it is observed a reduction of 0.237g in 14m thickness difference between the shallower profile (6.00m) and the deepest one (20.00m), while for the simulation in conditions of 100kPa constant matric suction, the reduction is 0.102. A reduction from 44% to 70% in the *PGA* values from 25kPa to 100kPa matric suction profiles could be mentioned for the ground response. Partially saturation conditions modifies the damping ratio and the nature of degradation of G/G_{max} of materials.

From these values, factor F_{PGA} is established, which corresponds to the relationship between the maximum acceleration produced in any layer with the maximum acceleration produced in the base $F_{PGA}=PGA_m/PGA_b$. This factor indicates whether the signal is amplified or attenuated in the soil profile, in relation to the magnitude of the signal in the rock. Figure 7 shows the calculated values of this factor for the soil profiles analyzed and the respective matrix suctions to which they were subjected.

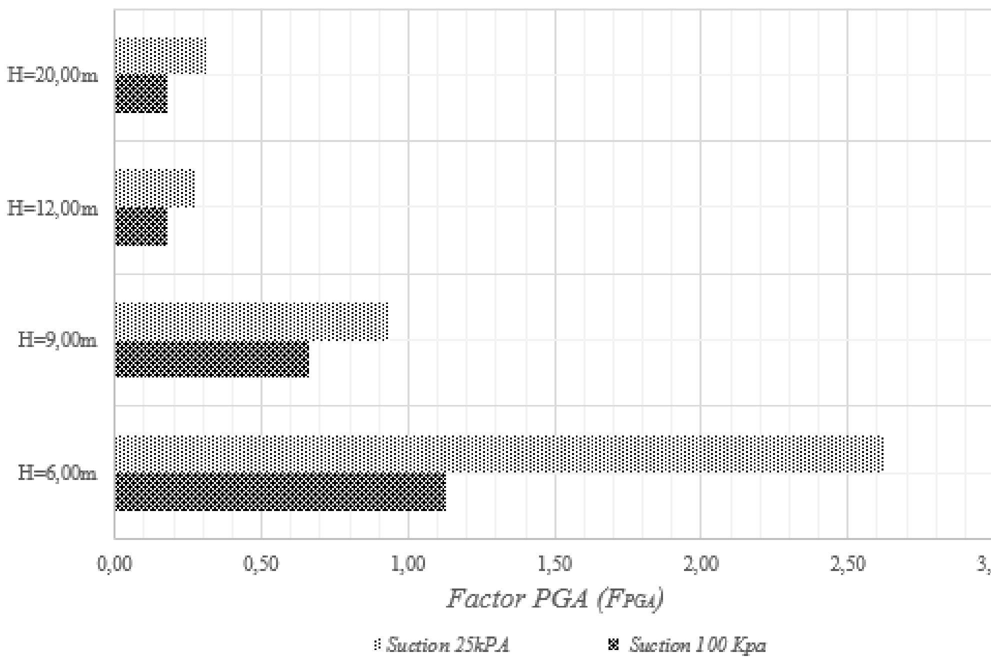


Figure 7. F_{PGA} values for each of the thicknesses modeled in the given matrix suction conditions

As shown in figure 7, F_{PGA} decreases with increasing soil profile thickness , indicating that accelerations produced by the earthquake on the surface decreases in both cases. The effect of the matric suction on the F_{PGA} factor is evident when observing that the values increase with smaller suctions.

The observed trends for the parameters analyzed in this paper in relation to the effect of suction vary substantially with that found by other researchers in similar materials (Biglari and Ashayeri 2013; Ghayoomi and Mirshekari 2014; Mirshekari and Ghayoomi 2017), which lie in an inversely proportional relationship between the maximum acceleration and surface condition of suction imposed, it is also evident in the spectral parameters found, the difference in results would be linked to the variation in the thickness of the layer which intrinsically this being affected by confining pressures that vary with respect to depth, therefore, the response is different. In relation to the F_{PGA}, the trend is similar to that obtained by (Ghayoomi and Mirshekari 2014) where this factor tends to decrease with increasing depth, however, a direct comparison probably is inappropriate because this factor depends on the acceleration history occurring in the base (rigid material or rock), and earhtquake characteristcs.

4. CONCLUSIONS

According to the results of one-dimensional simulations carried out in this work, four essential conclusions can be presented:

- It is evident that the thickness of a soil deposit is an important variable that influences the energy dissipation of an earthquake, even when there are conditions of partial saturation and matric suction. This could be explained because the net confinement pressures *(p-U_a)* directly affect the dynamic properties and damping characteristics of the materials present in the profile, so it is important to include this variable in the dynamic response analysis.

- The influence of thickness shows an inversely relationship with the generation of *PGA* values and spectral accelerations *(S_a)* on surface, this relationship is presented in the same way with the F_{PGA} factor, however the variability of those parameters depends on the conditions and dynamic characteristics of the material that is taken as a basis for seismic analysis.

- The effect of the matric suction is reflected in the rate of change for the accelerations that are generated on the surface with the variation of the thickness, for higher matric suction the acceleration values are lower for the same layer, while for low suction, surface accelerations are greater, from this tendency it is possible to infer that energy dissipation during seismic earthquake occurs more quickly with increments of matric suction in soil profiles.

- According with tendencies and results presented in this work, it is important to continues investigations on the seismic response of soils, taking into account a greatest number of variables that may influence the spectral response, in order to generate scenarios that are increasingly closer to the real situations of natural, partially saturated soils.

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