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Influence of foundation embedding on clays shrinkage-swelling hazard consequences

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ABSTRACT: Shrinkage-swelling of clayey soils is a natural hazard, which may significantly affect buildings by differential settlements. In this paper we studied the foundation settlement caused by this geohazard for buildings constructed on expansive soils and subjected to a drought period. A soil-structure interaction model was proposed. The hydro-mechanical coupling was taken into account by using the state surface approach. Settlement was evaluated according to foundation depth and a mean building stiffness. The uncertainties related to the choice of the state surface or the environmental factors were considered by using the Monte-Carlo approach. This paper highlights the interest of deeper foundations to reduce the building vulnerability towards this geohazard on expansive soils.

Keywords: Shrinkage-Swelling, Soil Structure Interaction, Foundation depth, Building Stiffness.

1 INTRODUCTION

Shrinkage-swelling of clayey soils is a costly geohazard throughout the world. The study of its impact on buildings for risk management raised many questions, because of the very complex hydro-mechanical behavior of clayey soils and the occurrence of soil-structure interaction phenomena.

The assessment of the ground settlement (or uplift) due to shrinkage (or swelling) under a foundation is a key point to study the building behavior and the associated damages. For clayey unsaturated soils, this ground movement is a consequence of both the variation of suction due to weather conditions (hydraulic part) and the variation of vertical stresses (mechanical part) due to the soil-structure interaction, with a coupling between the hydraulic and mechanical parts. Due to soil spatial variability of hydraulical and mechanical properties, occurrence of shrinkage-swelling hazard of clayey soils leads to differential settlement beneath the foundation which ends up to cracks in facades and structural elements, especially in unreinforced masonry elements.

Vertical stresses transmitted by the building to the ground, change during ground settlement according to the building stiffness. A flexible building could follow the ground settlement with minor changes in the transmitted stresses, while a stiff building can resist and cause a new distribution of the vertical stresses.

The aim of this paper is to study the ground settlements under a foundation during a drying phase, taking into account the hydro-mechanical couplings to investigate the influence of foundation depth.

A simple model of soil-structure interaction was developed. The hydro-mechanical behavior of the soil was modeled by a state surface approach and the building stiffness by its flexural rigidity to take into account the reduction of stresses in the soil during its shrinkage. A Monte Carlo simulation was also applied to consider uncertainties of model's parameters and environmental factors.

2 DESCRIPTION OF THE MODEL

Masonry individual buildings with shallow foundations are most affected by the shrinkage-swelling of clayey soil, as they induce small stresses into the ground and as the maximum suction change occurs near to the surface (ie. near the bottom of foundations).

Generally suction variation is maximum at the extremity of the building, where the soil dries easily, and negligible at its center (figure.1-a). This leads to a differential settlement of the ground and the building between the center and the edges (figure.1-b and c). This differential settlement depends on the building stiffness, the suction variations beneath foundations, the foundation length and the ground hydro-mechanical properties.

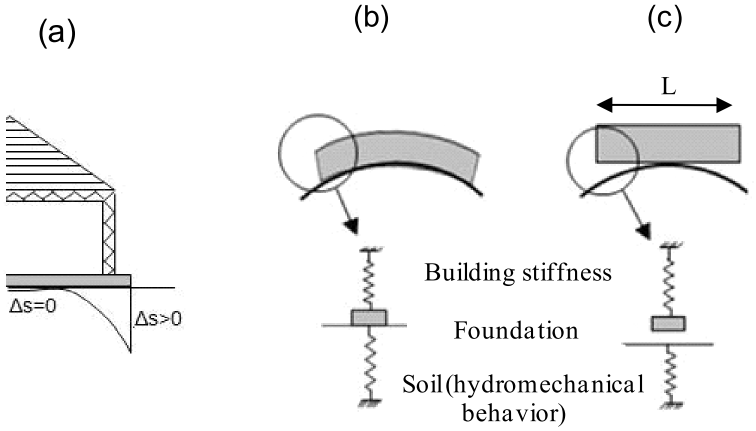

Figure 1. (a) Suction changes at the extremity of building. Soil-foundation interaction and the simplified model for (b) a flexible building, (c) a rigid building.

In this work the soil-foundation interaction at the edge of the building was investigated with a simple model described in figures 1b and 1c. The soil hydro-mechanical behavior was considered with a spring, which is modeled by a state surface (see section 3). The building stiffness is modeled by a spring with a constant stiffness (see section 4). This model is developed to deal with the effect of the foundation depth with respect to the building rigidity on the settlement of a foundation due to a drought period considering all other parameters that may influence the settlement.

In this model the soil was divided into several unit layers with a thickness of h_i = 0.1m, to take into account the suction and the stress variation with depth (Figure 2). The soil shrinkage Δe_i (variation of void ratio) at the middle of each layer is evaluated by the state surface approach taking into account the hydro-mechanical coupling and the soil-structure interaction (section 6). The final settlement of each layer Δh_i is then calculated and the total settlement of the ground surface is obtained with equation 1.

$$\Delta = \sum_{i=1}^{n} \Delta h_i = \sum_{i=1}^{n} h_i \frac{\Delta e_i}{1+e_{0i}} \tag{1}$$

where e_{0i} is the initial void ratio of the layer i, Δe_i the variation of void ratio and h_i the initial thickness of the layer i.

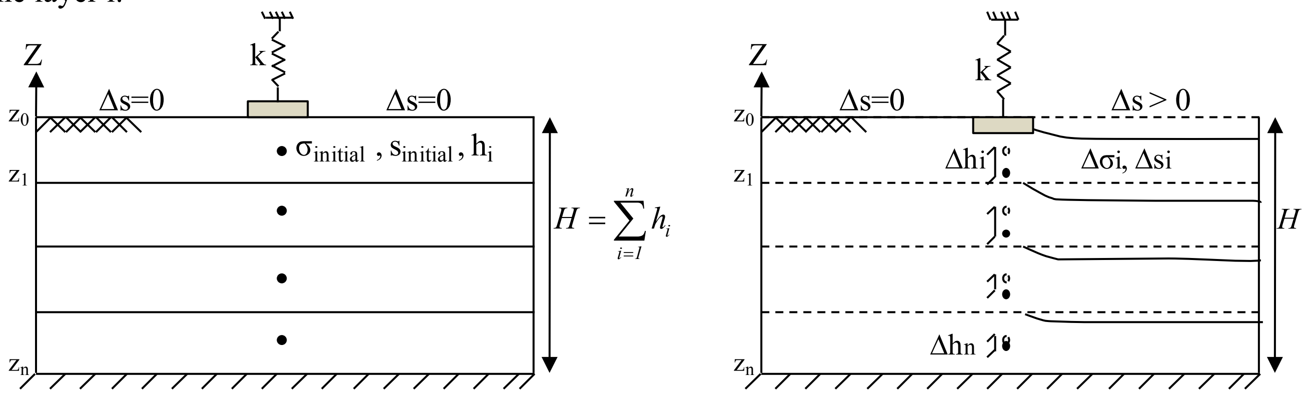

Figure 2. (a) Initial state of layers, (b) final state of layers after undergoing the suction change.

3 MODELING THE HYDRO-MECHANICAL BEHAVIOR OF SWELLING CLAYS

The amplitude of shrinkage-swelling of clayey soils is the sum of two terms: deformation due to the variation of the suction in the soil and deformation due to the changes of vertical stresses applied by the foundation. In addition, there is a coupling between the hydraulic and mechanical parts. Several authors have highlighted the unsaturated expansive soils hardening; as the increase of the mechanical load decreases the deformations due to the hydraulic variations (Alonso *et al.*2005; Nowamooz 2007; Airo Farulla *et al.*2010).

The influence of hydro-mechanical coupling on the amplitude of settlement under a foundation is modeled with the state surface approach. This concept explains the void ratio e as a function of the net stress $(\sigma-u_a)$ and the suction $s = (u_a-u_w)$, where u_a and u_w are respectively the air pressure and the water pressure in the soil and σ is the total stress.

Lloret and Alonso (1985) proposed several analytical functions of state surfaces for different types of slightly plastic soil. Vu (2003) proposed six functions to fit the void ratio constitutive surfaces of an unsaturated expansive soil and tested these functions on swelling clay of Regina (Saskatchewan - Canada). Herein, the function *Unsat-1* was considered because of its reasonable number of parameters (3 parameters) and for its ability to model the experimental results (equation 2).

$$e = a + b\log[1+(\sigma-u_a)+c(u_a-u_w)] \qquad (2)$$

where a is the void ratio at zero net stress and suction. Parameter b controls the total volume change due to suction and stress changes and the parameter c represents the rate of volume change during a variation of suction and may be related to the swelling characteristic of the soil, such as plasticity index (Vu 2003). The fitting parameters a, b, c can be obtained by oedometric or triaxial suction controlled tests.

Three different soils were chosen in this study: the clay of Regina (Vu and Fredlund 2007), the Jossigny silt (Fleureau et al. 2002) and the Boom clay (Alonso et al 1995). Table 1 presents different parameters of the considered state surface *Unsat-1*(equation 1) fitted on the experimental data for the first drying cycle for these three soils. Figure 3 shows the corresponding state surfaces. At the initial state (zero net stress and suction) the Jossigny silt appears to be dense while Regina and Boom clays are loose (parameter a). The Regina clay has a higher parameter c and also a higher value of the plasticity index (40%) than others. Consequently, the Regina clay is more expansive than two other soils and has the highest suction compression index (coefficient of compressibility with respect to suction changes). Among the studied soils, the Boom clay has the lowest coefficient of compressibility with respect to suction change, which means this soil is the less expansive.

Table 1. Numerical values of parameters of the state surface (equation 1), correlation coefficient of the regression, plastic index and dry density of the three investigated soils.

Soil parameters clay	*a*	*b*	*c*	R^2	*Ip(%)*	γ_d *(kN/m³)*
Jossigny silt (Fleureau et *al.* 2002)	1.12	-0.16	0.212	0.893	21	17.4
Regina clay (Vu and Fredlund, 2007)	1.186	-0.092	0.610	0.98	40	15.4
Boom clay (Alonso et al,1995)	1.61	-0.332	0.051	0.94	26.7	14

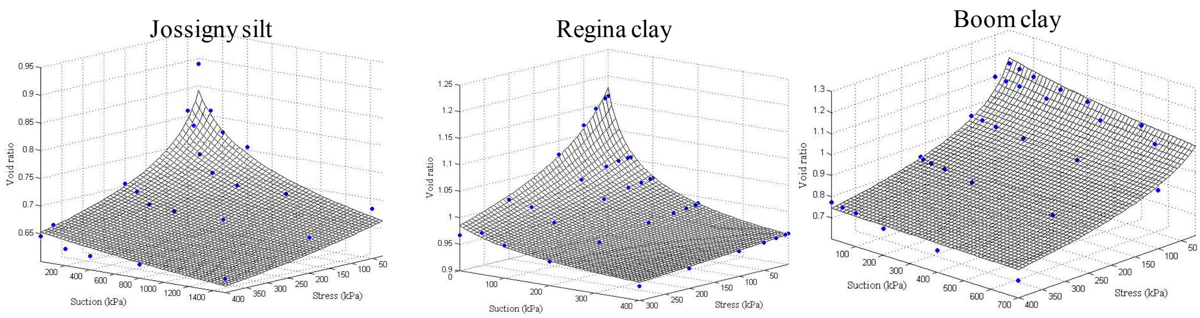

Figure 3. Comparison between experimental data and the fitted state surfaces for three studied soils.

4 MODELING THE BUILDING STIFFNESS AND VERTICAL STRESSES IN THE GROUND

To model the building stiffness, as a first approximation, the building can be considered as a horizontal beam resting on the ground (Figure 1-b and c). Ground shrinkage will lead to a decrease of vertical stresses under the building edges and a transfer of carried loads of the building to other parts of the soil, near the building centre. The final ground settlement Δ under foundations may be calculated by the approach of the state surface depending on the suction variation of the ground and the building stiffness (Figure 4).

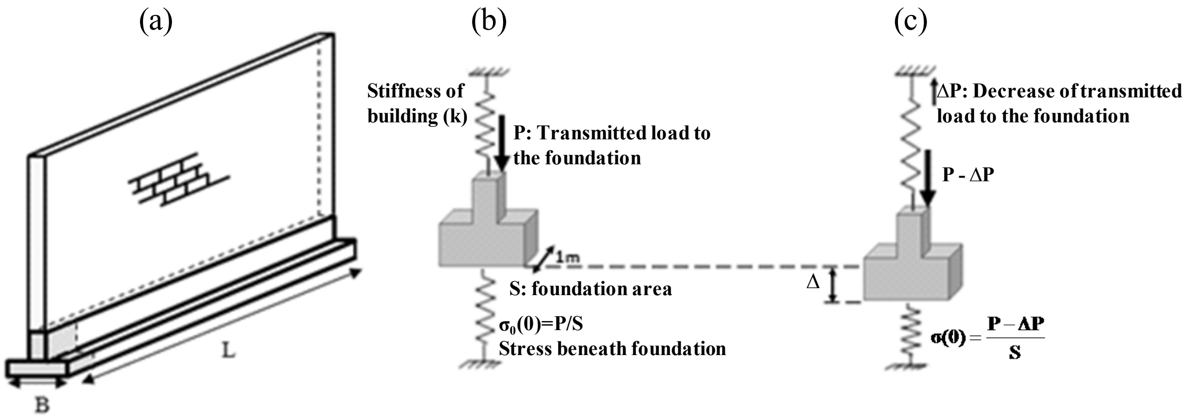

Figure 4. (a) Building flexural rigidity system composed of foundation (strip footing) and wall. Uni-dimensional model to study the soil-structure interaction, (b) initial state, (c) after undergoing the suction change.

The building rigidity system composed of foundation and wall is shown in the figure 4-a. In the proposed uni-dimensional model a length of one meter at the extremity of this rigidity system is isolated (figure 4-b). Then the influence of the structure is modeled by a spring with a characteristic stiffness *k* to estimate the applied stress variations in soil during its shrinkage (figure 4-c). Estimation of the value of *k*, which depends on rigidity and geometry of the building, is complex. The stiffness parameter *k* can be calculated by assuming that the building after undergoing the suction changes, acts as a cantilever beam of a length L/2. The stiffness can then be roughly assessed with EI/L^3, where *E* is the Young modulus of building, *I* is the moment of inertia and *L* the length of building (Frantziskonis and Breysse 2003, Denis 2007). For the calculation of I and E, some authors neglect the masonry wall stiffness compared to the foundation one, while some others take both into account (Bowles, 1997).

Possible values of k may be assessed by considering realistic values of these parameters: *E* between 5000 and 20 000 MPa (Dimmock and Mair 2008), *I* between 0.1 m^4 (inertia of the foundation) and 5 m^4 (inertia of both the wall and foundation) and *L* between 5 and 15m. These result into a range of variation of *k* between 1MN/m (flexible building) and 5 MN/m (rigid building).

In the first part of calculation a mean building stiffness (2.5 MN/m) was considered to study the effect of foundation embedding towards the occurrence of shrinkage phenomenon. Afterward the uncertainties coming from estimation of building stiffness will be treated in the probabilistic section.

When the foundation follows soil shrinkage (Figure 4-c), the stress in the soil surface can be calculated by equation 3:

$$\Delta P = k \times \Delta$$
$$\sigma(0) = \frac{P - \Delta P}{S} = \frac{P - k \times \Delta}{S} \tag{3}$$

where *σ (0)* is the vertical stress transmitted by the foundation to the ground at zero depth under the foundation, Δ is the settlement due to soil shrinkage, *S* is the foundation area and *P* is the building load. For each ground layer under the foundation, vertical stresses are the sum of geostatical and loading stresses. Geostatical stresses $\sigma_{geo}(z)$ are due to the weight of soil and linearly increase with depth (equation 4). Loading stresses $\sigma_{load}(z)$ are due to the building weight and decrease with depth because of the stress diffusion under the foundation. The decrease of stresses in the soil layer with the increase of the depth is calculated with Bousinesq relationship (equation 5).

$$\sigma(z) = \sigma_{load}(z) + \sigma_{geo}(z)$$
$$\sigma_{geo}(z) = \gamma_d \times (z) \tag{4}$$

$$\sigma_{load}(z) = \frac{\sigma(0)LB}{(L+z)(B+z)} = \frac{(\frac{p - k \times \Delta}{S})LB}{(L+z)(B+z)} \tag{5}$$

Where *B* is the width of the foundation (strip footing), *L* is the length of the foundation, *z* is the considered depth under the foundation level and γ_d is the dry density.

5 SUCTION PROFILE

Ground settlement of clayey soils is dependent on the suction profile and increases when the suction increase goes deeper into the ground. Generally the suction change is maximum at the ground surface, where it can reach a few MPa and decreases with depth. The suction profile is dependent on many parameters as: the soil characteristics (nature, structure, particle size, retention curve, permeability etc.), the meteorological parameters (precipitation and evaporation rate) and local conditions as the presence of vegetation etc. To quantify the soil shrinkage and the settlement magnitude, it is necessary to quantify the suction variation and the active depth where the suction change is not negligible under the foundation. In this study a linear suction profile was considered and the uncertainty coming from the suction profile was not taken into account. This problem is explicitly discussed by different authors (Mitchell 1979, McKeen and Johnson 1990,, El-Garhy and Wray 2004, Aubeny and Long 2007, etc). The choice of linear suction profile could be considered as a mean profile by using of equation 6:

$$s(z) = \Delta s(1 - z / z_a) \text{ for } z<z_a \tag{6}$$

where z is the depth; $s(z)$ is the suction value at the depth z; Δs is the magnitude of suction change at the ground surface and z_a is the active depth which is fixed to one meter in this study.

6 RESOLUTION FOR THE CALCULATION OF THE FINAL SETTLEMENT

Calculations of the final equilibrium state and the final settlement of each ground layer may be obtained by combining equations of the state surface (equation 2), of the vertical stresses in each ground layers (equation 5), suction amplitude in each layer (equation 6) and of the layer shrinkage in relation to the change of the void ratio (equation 1). Equation 7 presents the settlement of each layer and the final settlement at the ground surface is the sum of all layer's settlement.

$$\Delta h_i(z) = h_i \times \frac{bLog_{10}(1+\sigma(z)+c\times s(z)) - bLog_{10}(1+\sigma_0(z))}{1+a+bLog_{10}(1+\sigma_0(z))} \tag{7}$$

where $\sigma_0(z)$ is the initial vertical stress at the depth z before any suction variation, calculated with equation 8:

$$\sigma_0(z) = \frac{(P/S)LB}{(z+L)(z+B)} + \sigma_{geo}(z) \tag{8}$$

In this paper the total height H of the clayey soil concerned by the suction variation is divided into 10 sub-layers where the suction value $s(z)$ and the stress state $\sigma(z)$ are determined at the center of each layer.

7 RESULTS

To study the influence of the depth of the foundation over the amplitude of the final settlement, five depths were considered (0 until 0.5m). These shallow depths were taken into account according to a study carried out by Fondasol Company (2009) that showed numerous buildings that have been affected by the drought hazard in France, had the foundation depth lower than 50 cm.

Figure 5-a shows the evolution of the final settlement for the studied soils, for Δs=1MPa and a mean stiffness of 2.5 MN/m. Embedding the foundation in a higher depth avoids its exposition to high suction variations and decreases the final settlement. The more expansive soil (Regina clay) products the higher amplitude of settlement, while the less expansive one (Boom clay) result in smaller settlement. Moreover figure 5-b shows that the influence of the foundation depth is similar for all the studied soils. In other words, the global influence of the foundation depth is not dependant on the ground. For all the studied soils, a 50 cm foundation depth decreases of the final settlement around 70% compared to the case of a zero depth.

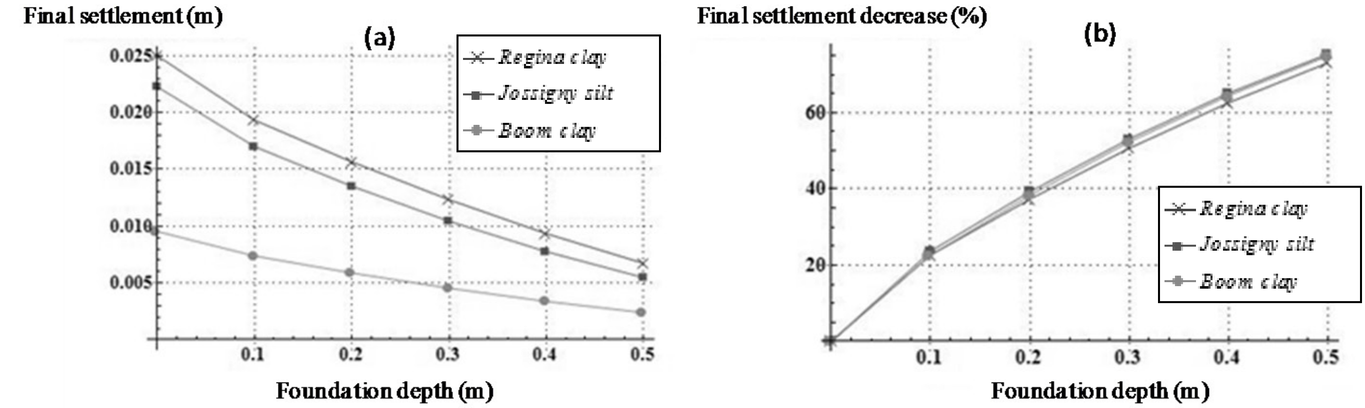

Figure 5. Foundation embedding effect (a) final settlement for the studied soils, (b) percentage of the settlement decrease with depth is similar for all the studied soils.

8 PROBABILISTIC APPROACH

In this section, we consider different uncertainties on the choice of the state surface and its parameters, the building stiffness, environmental factors (as the suction at surface). A Monte-Carlo simulation is then used to assess the variability of the results presented in Fig. 5.

8.1 *Uncertainties due to the choice of the state surface*

Different state surfaces are proposed in the literature (Lloret & Alonso; 1985, Vu & Fredlund; 2007, etc.). Herein four state surfaces were considered (one already used in the previous section) and fitted on experimental data of the three studied soils. Mathematical expressions of the state surfaces and final fitted parameters are shown in table 2. Four calculations were performed considering the different state surfaces of table 2. Results of the final settlement are plotted in Figure 6-a with the standard deviations bar. These results show that the final settlement value can be overestimated or underestimated depending on the chosen state surface. Figure 6-b shows that the mean value of the percentage of settlement decrease is less important for the less expansive soil (Boom clay), with a maximal value of 60% and can rise until 75% for the most expansive soil (Regina clay).

Table 2. Numerical values of parameters for the four considered state surfaces and the three investigated soils.

	Function	Fitting Parameters		
		Jossigny silt	Regina clay	Boom Clay
Fredlund (1979)	$e = a + b\log(\sigma - u_a) + c\log(u_a - u_w)$	a =1.12; b = -0.165; c = -0.035	a =1.186; b = -0.063; c = -0.041	a =1.61; b = -0.301; c = -0.041
Lloret & Alonso (1985)	$e = a + b\log(\sigma - u_a) + c\log(u_a - u_w) + d\log(\sigma - u_a)\log(u_a - u_w)$	a =1.12; b = -0.1767; c = -0.093; d = 0.006	a =1.186; b = -0.091; c = -0.083; d = 0.034	a =1.61; b = -0.300; c = -0.039; d = 0.001
Vu -a(2003)	$e = a + b\log(1 + (\sigma - u_a) + c(u_a - u_w))$	a =1.12; b = -0.180; c = 0.228	a =1.186; b = -0.092; c = 0.610	a =1.61; b = -0.332; c = 0.051
Vu-b (2003)	$e = a + b\log\left[\dfrac{1 + c(\sigma - u_a) + d(u_a - u_w)}{1 + f(\sigma - u_a) + g(u_a - u_w)}\right]$	a = 1.12; b = -0.246; c = 0.358; d = 0.144; f = 0.001; g = 0.001	a = 1.186; b = -0.2763; c = 0.097; d = 0.015; f = 0.013; g = 6.317×10^{-5}	a = 1.61; b = -0.358; c = 0.632; d = 0.042; f = 2.22×10^{-14}; g = 2.22×10^{-14}

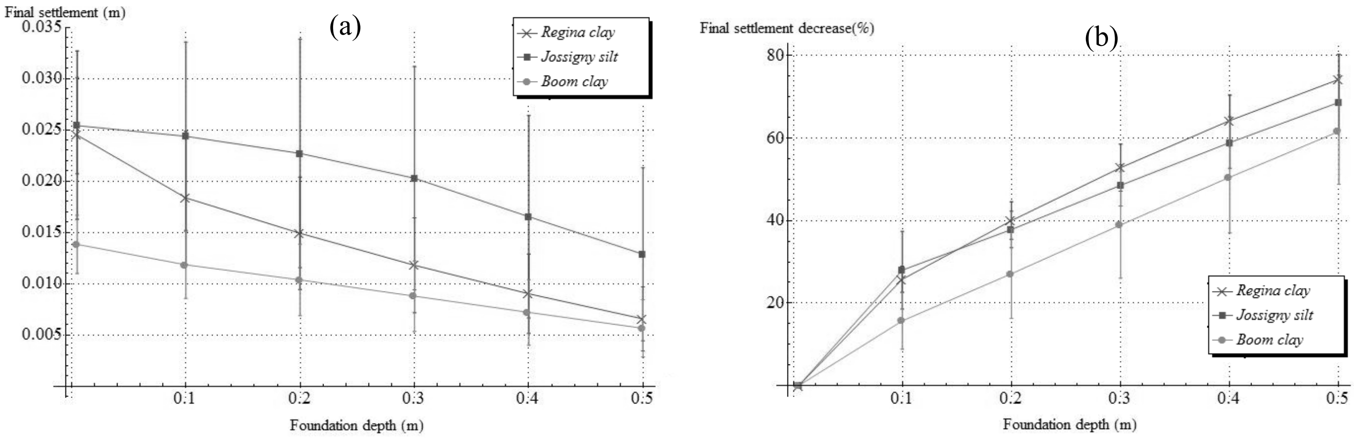

Figure 6. Considering the uncertainty coming from the choice of state surface (a) final settlement for the studied soils, (b) mean value of the percentage of settlement decrease with augmentation of foundation embedding depth.

8.2 *All parameters variability*

In this section the variability of all parameters was considered, including the building stiffness (between 1 and 5MN/m; see section 4), the type of state surface, and the variation of suction at the soil surface. The variation of suction at the ground surface is considered between 0.5 MPa (usual drought period) and 2 MPa (exceptional drought period, Long; 2006). A Monte-Carlo simulation was performed 1000 times for a triangular statistical distribution considering suction changes and building stiffness variations. For each simulation the state surface type was chosen randomly.

Figure 7-a, shows the average value and the standard deviation of final settlement with the foundation depth. The foundation depth appears to have an important effect on the decrease of the settlement amplitude for all studied soils considering all uncertainties of model. For the most expansive soil this effect is more significant.

Figure 7-b illustrates the percentage of settlement decrease, which could rise to 70% for the most expansive soil and to 60% for less expansive ones considering an increase of foundation depth from 0 to 50 cm.

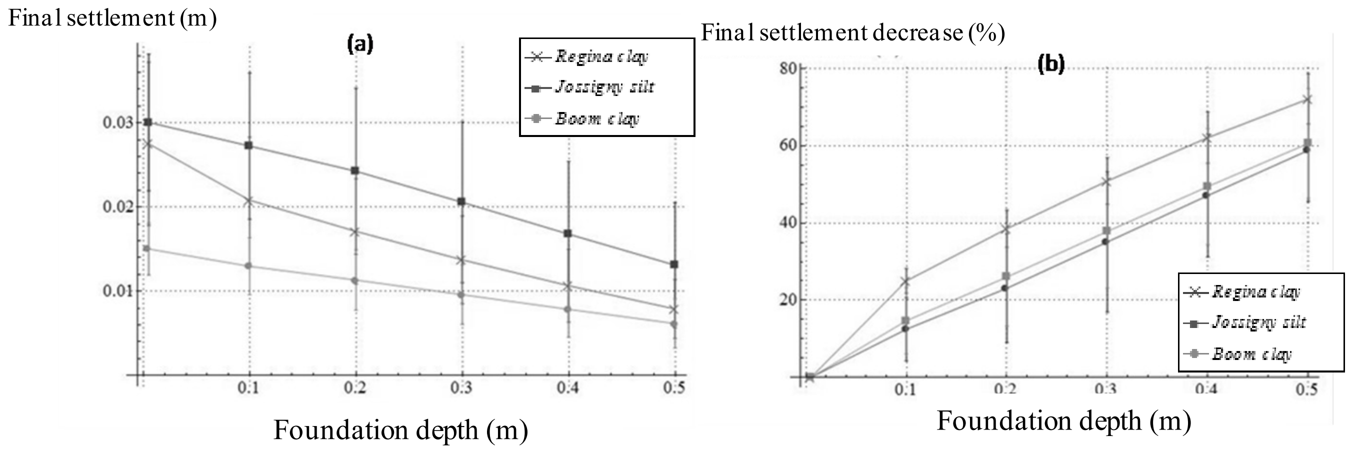

Figure 7. Considering the uncertainty coming from the variability of all the parameters of model, (a) final settlement, (b) Percentage of settlement decrease with augmentation of foundation embedding depth.

9 CONCLUSIONS

A simple method was developed to investigate shrinkage-swelling and soil-structure interaction for clayey soils. This methodology considers the hydro-mechanical coupling of unsaturated clayey soils with the state surface approach, and allows assessing the settlement under foundation due to a drought in relation to the building stiffness, suction vertical profile, suction change intensity and depth of foundation.

Investigation of the influence of foundation depth showed that the increase of the foundation embedding depth, from 0 to 50cm can decrease the amplitude of potential settlement due to drought of about 60 % to 70 % for respectively less expansive and very expansive soils. The results of probabilistic analysis were in agreement with the general effect of foundation embedding depth on the amplitude of settlement due to shrinkage. The model can also be used to estimate the mean value of the final settlement for a group of buildings having the same stiffness and foundation depth, constructed on a site with soil characteristics that displays small variability, and undergoing a drought period.

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