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An analytical model of soil–structure interaction with swelling soils during droughts

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ABSTRACT

Lightly loaded structures constructed on expansive soils may develop structural damage as a result of changes in the soil's moisture content. This study investigated an analytical model of soil–structure interaction to assess the settlement of dwellings built on swelling soils when droughts occur. The building behavior was investigated with the Euler–Bernoulli beam theory, and the ground behavior was investigated with a Winkler-derived model based on the state surface approach. The analytical model results were compared to those of a finite element analysis using the Barcelona Expansive Model (BExM) performed with Code_Bright.

The analytical model was then used to assess the settlement transmission ratio for a typology of clayey soils and different parameters of building. The results indicated that the final deflection of the building increased with the building length and soil suction. The building deflection due to the suction variations was inversely proportional to the load, the rigidity of the building and the embedding depth of the foundation. Increasing these parameters made the building less vulnerable to shrinkage and swelling action.

1. Introduction

Shrinkage and swelling of clayey soils are known to be costly geohazards around the world. The study of their impacts on buildings for risk management has raised many questions because of clayey soils' complex hydro-mechanical behavior and susceptibility to the soil–structure interaction phenomenon. In moderate climates such as that of France, the soil is usually close to its saturated state, and the maximum volume changes in soils occur during dry seasons, when the changes in water content are greatest. These volume changes cause differential settlements beneath foundations due to different variations in moisture content under the edges of a building and its center.

A better understanding of the behavior of swelling soil and a building undergoing a drying (or wetting) phase is therefore crucial to the effective design of shallow foundations and buildings on swelling soils and to assessing existing buildings' vulnerability. In unsaturated clayey soils, the ground settlement during a drying (or wetting) phase is a consequence of both the variation in suction (negative pressure in soil) due to weather conditions (the hydraulic part) and the variation of vertical stresses due to soil–structure interaction (the mechanical part), with a coupling between the hydraulic and mechanical parts.

The hydro-mechanical behavior of unsaturated expansive soils has been studied by several authors (e.g., [2–6]). They have concluded that the swelling behavior of unsaturated expansive clays can be described as a coupled response of the soil to suction changes and applied stresses. Few models integrate this coupled hydro-mechanical response into a unified framework, but one commonly used model that does is the Barcelona Expansive Model (BExM), proposed by Alonso et al, with 22 parameters [1]. This model can be considered as a theoretical reference framework for the study of the expansive behavior of unsaturated clays. The state surface approach, which is a simpler but efficient method of linking the volume change to two independent stress state variables, net stress $(\sigma - u_a)$ and suction $(u_a - u_w)$, was proposed by Matyas and Radhakrishna [7] and has been used by other authors [3,5,8–11]. These researchers have shown that net stress and suction, as the stress state variables, are necessary to describe the hydro-mechanical behavior of an unsaturated soil. The state surface approach has been used as a simplified method for solving practical problems with a simple stress path [12]. However, because this approach has a unique constitutive surface, it cannot be used to describe the effect of stress-path and hysteresis behavior.

Fredlund and Morgenstern [8] performed a series of monotonic loading stress paths on unsaturated swelling Regina clay and concluded that a unique state surface can be considered under

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monotonic loading conditions. However, each cycle requires a separate state surface in the case of cyclic hydraulic solicitations. Zhang and Lytton [12] recently presented a modified state surface approach that considers stress-path dependency and suction-hardening behavior. This approach produced results similar to those obtained using the BExM model. Some authors [12–14] have reported that estimating volume change using the state surface approach is adequate for most engineering analysis.

Building damage due to ground movements is most commonly associated with differential settlement [15,16]. However, differential settlement is a consequence of soil–structure interaction and cannot be assessed without accounting for the mechanical behavior of the soil and the structure. Many researchers modeled the building as a beam resting on the ground [16–19] to assess the transmission ratio of ground movements to the building. Depending on the building stiffness, the vertical stresses transmitted by the building to the ground change during ground settlement (soil–structure interaction). A flexible building follows the ground settlement with minor changes in the vertical transmitted stresses, while a rigid building can resist settlement and cause a redistribution of the vertical stresses under the foundations. Consequently, a transmitted deflection ratio Δ/Δ_0 is defined ([17,19]) as the ratio between the building deflection Δ due to the ground movements with soil–structure interaction and the deflection Δ_0 calculated using the free-field ground movement without any soil–structure interaction. Δ_0 is then calculated under the assumption that the free-field ground movements are integrally transmitted to the building (Fig. 1).

The differences between free-field ground shrinkage and building-induced deflection depend on the ground and building stiffness, the building length, the vertical load, the foundation depth and the swelling capacity of the soil.

Existing soil–structure interaction models for expansive soils are mostly based on the Winkler model and consider the ground's initial mound shape due to shrinkage (or swelling). Nelson and Miller [20] have summarized these existing models, while other researchers [21,22] have estimated the shrinkage at the extremities of foundation slabs with empirical methods and have investigated the effect of the shaped form of the ground (due to shrinkage) on building behavior using numerical methods. In such a framework, the influence of vertical stress changes beneath the foundation during the shrinkage phase on the hydraulic parameters of the soil is not included when calculating the final transmitted settlement.

The focus of this study was on the role of soil–structure interaction in hydro-mechanical coupling. The building's mechanical behavior was modeled using Euler–Bernoulli beam theory, and the hydro-mechanical behavior of the soil was modeled with the state surface approach. The challenge in the proposed model was to incorporate the hydro-mechanical behavior of clayey soils undergoing water content changes in classical soil–structure interaction models.

In this study, the deformation due to the loading phase was assumed to have been stabilized before the drying phase [23] to study the existing building's behavior. Only the settlement (shrinkage) caused by the drying phase was considered to study the consequences of drought on the building. The soil was considered to be a homogenous and isotropic medium, and its variability beneath the building was not considered.

The following sections describe the different components of the model:

- the hydro-mechanical behavior of swelling clays, modeled with the state surface approach;
- the vertical and horizontal suction change profile in the soil;
- the building stiffness and vertical stress in the ground, modeled with the Euler–Bernoulli beam theory and Boussinesq relation; and
- the combination of the different models and solution of the constitutive equation.

2. Description of the model

Fig. 1 shows a schematic of building deflection induced by soil shrinkage during a drying period.

When a drying period occurs, the suction variation is greatest at the extremity of a building, where the soil dries easily, and is negligible at the center of the building [24]. Fig. 1b shows the distance e_m under the building undergoing the suction variations. The active depth z_a over which the suction varies is not negligible. This change in suction content leads to a differential settlement of the ground and the building between its center and its edges (Fig. 1c).

The suction profile of soil is dependent on parameters such as the soil's characteristics (nature, structure, particle size, retention curve, permeability, etc.), meteorological parameters (precipitation and evaporation rate) and local conditions, such as the groundwater level, the presence of vegetation, etc. The building can also affect the evolution of a suction (or moisture) profile. This evolution is discussed further in Section 2.3.

In the proposed model, the ground was divided into several layers to account for variations in suction and vertical stresses with depth (Fig. 1). The void ratio variation Δe_i was calculated at the middle of each layer with the state surface approach by considering hydro-mechanical coupling (Section 2.1) and soil–structure interaction (Section 2.4). The final settlement of each layer Δh_i was then calculated, and the total settlement of the ground surface was obtained using following equation.

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

where e_{0i} is the initial void ratio of layer i, Δe_i is the variation in void ratio, and h_i is the initial thickness of the ith layer. Fig. 1 shows a general schematic of the model in its initial state (Fig. 1a) and after undergoing suction variation (Fig. 1b and c). The model was

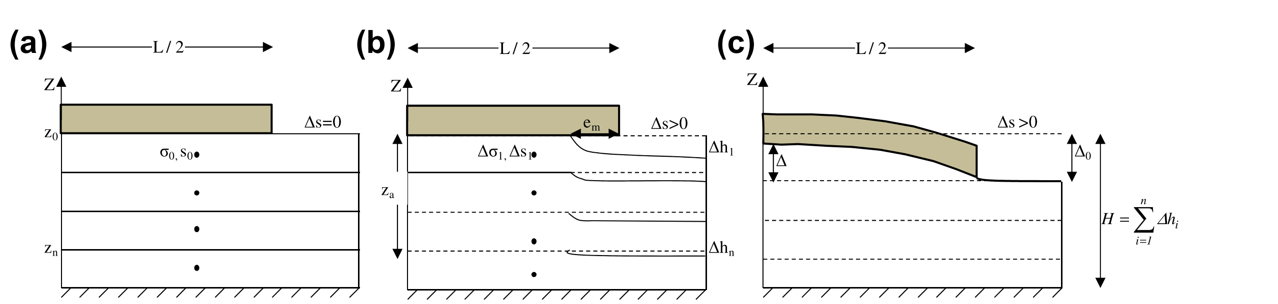

Fig. 1. Building deflection induced by soil shrinkage during a dry period: (a) Initial state of layers, (b) drying evolution under the building, and (c) final state of layers after undergoing suction and final building deflection (e_m: edge moisture change, Z_a: active depth, Δ_0: free field settlement, Δ: building deflection).