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# Clay soil settlement: In-situ experimentation and analytical approach

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**Abstract**

On the basis of the existing relationship between soil structure and water content, and in order to avoid the multiple factors influencing the study of soil behavior in the laboratory, a full-scale in-situ testing was performed in Ouarzazate (Morocco) to quantify the soil vertical displacements according to the environmental conditions.

The study presented in this paper is devoted to analyzing the load-settlement relationship of active clay soil during the drying process. A time-dependent model is presented to quantify the soil settlement amplitude according to the hydraulic and mechanical states of the soil mass.


*Keywords:* Vertical displacements; Shrinkage; Settlement; Clay soil; Predicting model; In-situ testing

## 1. Introduction

The total volume change observed in expansive clay soils is basically due to the respective changes associated with each component phase. The interdependence of the physical and chemical processes that occurs in the soil mass, however, leads to the complex mechanics of volume change. This volume change can be defined as a coupling of hydraulic and mechanical processes; deformation resulting from the variation of the water content due to weather conditions represents the hydraulic part, and deformation resulting from the variation of vertical stresses due to the soil–structure interaction represents the mechanical part. To simplify the analytical approach of problematic volume changes, Gens and Alonso (1992) presented a conceptual basis for a model for expansive soils, where two distinct levels are distinguished: a microstructural level where the swelling of active minerals takes place, and a macrostructural level responsible for major structural rearrangement. At the microstructural scale, volumetric stress–strain behavior is considered, while volumetric and deviatoric effects are considered in the macrostructural scale. On the other hand Annette (1998) presented a model where the strain increment in a small time step has two components: an elastic increment which is the direct response to changes in an effective stress state and a plastic increment which is a time dependent response. Mitchell and Soga (2005) presented an analytical model which describes an attempt to combine both elastic and plastic behaviors; it is assumed in this model that the strain is a sum of the elastic and plastic components (cited by Nelson and Miller (1992)).

The Barcelona Expansive Model (BExM) proposed by Alonso et al. (1999) is considered as a theoretical reference framework to study the behavior of unsaturated expansive clays. In the literature several prediction models were developed to assess the volume changes coupling the hydraulic and stress states (Ejjaaouani et al., 2008; ARGIC-BRGM/RP-54862-FR et al., 2006; Mitchell and

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Soga, 2005; Rees and Thomas, 1993; Alonso and Lloret, 1982; Fredlund and Rahardjo, 1993), and the study of the time-dependent behavior of clay soils remains one of the most discussed approaches used to quantify their long term behavior. Alonso et al. (2005), Nowamooz (2007), Oka et al. (2010) and Wang et al. (2013) have highlighted the unsaturated expansive soils' densification, as the increase of the mechanical load decreases the deformation due to the hydraulic variations. However, it is more or less considered that most of the analytical models are developed for a specific environment or a specific kind of soil, and this is mainly due to the significant mineral associations and environmental conditions.

In arid and semi-arid areas like the studied field (Ouarzazate), active clays are in general associated with water deficient conditions, which means they are considered unsaturated soils. According to Popescu (1986), due to the development of a theoretical framework for unsaturated soils and of several models, expansive clay soils are treated as if they were unsaturated soils although the fundamental mechanisms of their volume change behavior are different. However, it is assumed that they exihibit identical behaviors during the drying process. This will be taken into consideration in the proposed prediction model presented in this paper.

In order to provide a contribution to quantify the settlement of clay soil, an analytical model is presented in this paper on the basis of a full-scale in-situ test performed by the Laboratoire Public d'Essais et d'Etudes (LPEE) and the Laboratoitre Central des Ponts et Chaussées (LCPC). Since the experimental device used in this experiment was not developed to assess the three dimensional deformations, only axial deformation measurements were allowed.

## 2. Materials and methods

### 2.1. Experimental device and experimentation

The in-situ tests were performed in the northwestern part of Ouarzazate city (Morocco), a location renowned for its reported structural damage. The expansive clay layer subjected to the experimental study is located from 0.5–1.7 m to 2.2 m under the ground level, and the thickness of the studied layer was not uniform.

The mineralogical description of the clay fraction of the studied layer is as follows:

- 10–15% illite;
- 25–40% kaolinite;
- 5–15% palygorskite;
- 45–55% smectite.

The main geotechnical properties of the studied layer are summarized in Table 1. Intact soil specimens were collected at a depth of 20 cm from the embedment level of the tested clay layer in order to characterize the soil parameters for each moisture state. A summary of the internal friction angle according to the soil moisture state and the soil vertical displacements is included in Table 2. The internal friction angle values were determined from the direct shear test, according to the French Standard NF_P94-071.

After removing the non-expansive covering layer, the developed experimental device consisting of four rigid foundations (one square meter for each one) was placed over the clay layer as presented in Fig. 1. A rotating steel beam fixed to the center of the experimental area served as the loading equipment, and the rotative movement of the loading beam allowed it to be placed over each foundation independently and a load was applied with a hydraulic jack with a 380 $cm^2$ surface. Each foundation was used at a certain moment of the experiment, relative to a specific moisture state. For the moistening stage, the water supply was possible thanks to small pipe lines placed over the entire tested area (water supplying network, Fig. 1), and the entire test area was submerged until a saturated steady state was reached.

Table 1
Physical and mechanical soil characteristics.

| Plasticity index ($I_p$) | Liquid limit ($W_L$) | Shrinkage limit ($W_s$) | Plasticity limit ($W_p$) | Blue methylene value ($V_{bs}$) | Soil's dry density ($\rho_d$) | Soil's density ($\rho_h$) |
|---|---|---|---|---|---|---|
| 30% | 57 | 16 | 27 | 5.12 g/100 g | 1.61 t/$m^3$ | 1.81 t/$m^3$ |
| Grading curve characteristics | Void ratio ($e$) | Liquidity index ($I_L$) | Swelling pressure ($\sigma_g$) | Free swelling deformation ($\varepsilon_g$) | Particles density ($\rho_s$) | Natural water content ($W$) |
| $C_2$ μm = 10%, $C_{20}$ μm = 80%, $C_{80}$ μm = 93%, 2 mm = 100% | 0.662 | −0.482 | 380 kPa | 0.114 | 2.66 t/$m^3$ | 12.5% |

Table 2
Water content and vertical displacement (Ejjaaouani et al., 2008).

| Foundation | Test date | Water content (at −20 cm) | Free swelling (mm) | Free settlement (mm) | Active zone thickness (m) | Internal friction angle ($\phi$) |
|---|---|---|---|---|---|---|
| FS-1 | Oct 2002 | 12.54% | – | – | 1.7 | 35 |
| FS-1 | Jul 2003 | 35% | 93 | – | 1.7 | 24 |
| FS-2 | Sep 2003 | 27% | 76 | 4–6 | 1.6 | 26 |
| FS-3 | Mar 2004 | 20% | 87 | 20–29 | 1.5 | 27 |
| FS-4 | Sep 2004 | 16% | 80 | 35–50 | 1.45 | 30 |