# Volume Change Behavior due to Water Content Variation in an Expansive Soil from the Semiarid Region of Pernambuco - Brazil

S.R.M. Ferreira, L.M. Costa, L.J.N. Guimarães, I.D.S. Pontes Filho

**Abstract.** One of the most important morphological characteristics of expansive soil is contracting and fissuring during drying and swelling during wetting. Soils that change volume when inundated with water require extra care, whether they are used in agriculture, engineering or both. In this paper, conventional and suction-controlled oedometric tests were used to evaluate the changes in volume and swelling pressure caused by changes in water content in an expansive soil from Petrolândia-PE. A coupled hydro-mechanical formulation, implemented in the computational code CODE_BRIGHT, was applied to simulate the tests performed with this soil. The constitutive model used was the double structure generalized plasticity model proposed by Sanchez *et al.* (2005). The results show that soil expansion, contraction and collapse depend on the initial water content and the external load applied. The conclusion is that volume changes due to water content variation are associated with the initial conditions of the soil and the load applied to the soil. The experimental data and simulation results are in good agreement, showing that the model and computer code are able to accurately represent the hydro-mechanical behavior of expansive soils.

**Keywords:** expansive soil, double structure model, hydro-mechanical coupled analysis.

## 1. Introduction

Expansive soils are characterized by their tendency to contract and fissure during drying and swell during wetting. The volumetric instability (contraction and expansion or collapse) of unsaturated soils upon inundation has complex causes and is affected by various factors. The instability depends on the type of soil (origin and formation), the presence of climatic determinants, the stresses affecting the soil and other factors. The use of expansive soils in construction projects can cause serious damage (fissures, ruptures and cracks) to the buildings when the soils are not adequately analyzed during the project and construction phases.

Several types of soils are subject to the phenomenon of swelling. These types include soils derived from igneous rocks, primarily basalt, diabase, gabbro, pyroxene and feldspar, and soils derived from sedimentary rocks with the clay mineral montmorillonite, such as shales, marls and limestones, which disintegrate easily.

In Brazil, expansive soils are found in various regions of the country. In the Northeast, Vargas (1985) identified regions that appear in layers of Cretaceous formations, from the north of Bahia to Pernambuco and Ceará. Costa Nunes *et al.* (1982) highlighted the expansive soil in the large metropolitan region of Recife, Maria Farinha Formation, of the Barreiras Group. Ferreira (1988) studied expansive soils in several municipalities of Pernambuco. Gusmão Filho & Silva (1991) and subsequently Jucá *et al.* (1992), used laboratory tests and field instruments to study the behavior of expansive clay in a metropolitan area of Recife. The expansive soil of Recôncavo was the focus of studies by various researchers: Sobral (1956), Simões & Costa Filho (1981), etc. In the Central South and South, expansive soils were found in superficial layers of the podzolic formations in Passa Dois and Tubarão Group in São Paulo, Parana and Santa Catarina, and also in the Santa Maria Formation in Rio Grande do Sul. Expansive soils are also found in Maranhão, Rio Grande do Norte, Alagoas, Sergipe, Mato Grosso. The geotechnical characteristics and the volume change response caused by wetting in the expansive soils of Brazil were analyzed by Ferreira (2008).

In expansive soils, volume changes caused by applied stress or suction are governed by various phenomena occurring at the microstructural level due to the interactions of individual clay particles with their surroundings. Gens & Alonso (1992) presented a conceptual basis for modeling expansive soil, in which two different levels are considered: the microstructural level, at which swelling of active minerals occurs, and the macrostructural level, which is responsible for major structural rearrangements.

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This paper analyzes the characteristics of volume variations due to changes in water content of an expansive soil from Petrolândia in Pernambuco, in the northeast of Brazil (520 km from Recife). The study site is located in Jatobá Basin. The local geology is represented by sediments of the Aliança Formation, which is composed of siltstones, shales and limestones of brown and reddish colors. The soil from this formation has clay or silt features, with dark colors that usually range from dark grey to reddish (Melo, 1980). In the field, desiccation cracks have been observed. This paper also utilizes a double structure model based on the work of Gens & Alonso (1992), which is implemented in a computer program to analyze the volume changes caused by changes in water content.

## 2. Materials and Methods

### 2.1. Geotechnical investigation program

The geotechnical investigation program was divided in two parts. In the situ part, undisturbed and disturbed samples were examined, and physical indices of the soil were measured. In the laboratory part, physical characterization tests were conducted in natural soil according to the methods of the Brazilian Association of Technical Standards (ABNT, 1984a; ABNT, 1984b; ABNT, 1984c; ABNT, 1984d), characteristic curve, microstructure (O-optic) and chemical analysis have been performed.

The volume changes associated with variations in the stress state and water content were analyzed through simple and conventional oedometer tests with controlled suction. Undisturbed samples with constant water content were statically loaded to a pre-determined stress level and then suction was progressively reduced.

In single oedometric tests, the applied vertical stresses were increased with the ratio $\Delta\sigma/\sigma = 1$. An initial stress of 10 kPa was used, and the stress was varied up to 1280 kPa. The time of each step was such that the deformation between consecutive time intervals ($\Delta t/t = 1$) was less than 5% of the total deformation that occurred up to the previous recorded time. The vertical deformations caused by inundation were measured at 0, 0.10, 0.25, 1, 2, 4, 8, 15, 30, 60, 120, 480 and 1440 minutes.

The swelling pressure was determined using three different methods: 1 - Loading after expansion with different vertical consolidation stresses, 2 - Expansion and collapse under stress, 3 - Constant stress (Justo *et al.*, 1984, and Ferreira, 1995).

Oedometric tests conducted with controlled suction had two stress paths. First, the undisturbed soil with natural water content was loaded until a certain vertical consolidation stress was reached (pressures of 10, 20, 40, 80, 160, 320, 640 and 1280 kPa were successively applied). In the second path, after stabilization of the deformation caused by vertical stress, the suction of the soil was reduced in stages (5.0, 2.5, 1.0, 0.5, 0.2 and 0.0 MPa), and the expansion deformation of the soil was measured. We sought to distinguish the vertical deformation caused by stress from that caused by reduced soil moisture (suction).

To analyze the pre-wetting and drying effects, undisturbed samples were molded in rings with a diameter of 101 mm and a height of 30 mm. The samples were placed in desiccators with different concentrations of sodium chloride or sulfuric acid for 10 months, and they were molded in rings with a diameter of 71.40 mm and a height of 20.0 mm for the simple oedometer test. To analyze the effect of desiccation on stress, undisturbed samples were molded and loaded to a pre-determined stress level, and the water content was allowed to decrease under stress at room temperature until the deformation stabilized, which occurred between 60 and 70 days.

### 2.2. Constitutive model

The constitutive model adopted in this paper is the double structure generalized plasticity model proposed by Sanchez *et al.* (2005), which is based on the general framework proposed by Gens & Alonso (1992) and incorporates improvements suggested by Alonso *et al.* (1999). Two levels of structure are considered. The macrostructural behavior is described by the Barcelona Basic Model (BBM), developed by Alonso *et al.* (1990). Other mechanisms not included in the BBM that occur in the microstructure at the clay particle level can occur in expansive soils and induce plastic strains. Thus, the double structure formulation includes the definitions of laws for the macrostructural level, the microstructure level and the interactions between both structural levels.

#### 2.2.1. Macrostructural model

The BBM considers two independent stress variables, the net stress, $(\sigma_{ij} - p_a\delta_{ij})$, and the matric suction, $s = (p_a - p_w)$. It is an elastoplastic strain-hardening model, which extends the concept of a critical state for saturated soils to unsaturated conditions, including the dependence of the yield surface on matric suction. The yield surface is expressed by

$$f(p, q, s, p_0^*) = q^2 - M^2(p + p_s)(p_0 - p) = 0 \tag{1}$$

with

$$p = \sigma_m - \max(p_a, p_w); \quad \sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \tag{2}$$

$$q = \sigma_1 - \sigma_3 \tag{3}$$

$$p_s = ks \tag{4}$$

where $\sigma_1$, $\sigma_2$ and $\sigma_3$ are the total principal stress, $M$ is the slope of the critical state line, $p_0$ is the apparent unsaturated isotropic preconsolidation stress for suction $s$, $p_0$* is the saturated preconsolidation stress and $k$ describes the increase of the apparent cohesion with suction. The net mean stress $p$ is defined as indicated in Eq. 2 to facilitate the transition from unsaturated to saturated states, $\sigma_m$ is the mean stress, $p_a$ is the air pressure and $p_w$ is the water pressure.

For isotropic conditions, the yield states associated with suction are described using a yield function defined in the space ($p$, $s$), which is named Loading-Collapse (LC). This yield function explains the collapse that occurs upon wetting and the increase in apparent pre-consolidation stress $p_0$ caused by suction. The relationship is expressed as

$$\frac{p_0}{p^c} = \left(\frac{p_0^*}{p^c}\right)^{\frac{\lambda(0)-\kappa}{\lambda(s)-\kappa}} \tag{5}$$

where $\kappa$ is the elastic stiffness parameter against changes in $p$, $\lambda(0)$ is the slope of the virgin compression line for saturated isotropic loading, $p^c$ is a reference stress and $\lambda(s)$ is the slope of the virgin compression line for isotropic loading at a constant suction $s$. The slope $\lambda(s)$ is defined as

$$\lambda(s) = \lambda(0)[(1-r)\exp(-\beta s) + r] \tag{6}$$

where $\beta$ controls the rate of stiffness increase with suction, and $r$ is a limiting value of soil stiffness for very high suction.

A non-associated plastic potential is defined by

$$g(p, q, s, p_0^*) = \alpha q^2 - M^2(p + p_s)(p_0 - p) \tag{7}$$

where $\alpha$ is established in such a way that under $K_0$ loading, lateral strains are zero.

The hardening parameter $p_0$* depends on the rate of volumetric plastic strain. The hardening law is given by

$$\frac{dp_0^*}{p_0^*} = \frac{(1+e)}{\lambda(0)-\kappa} d\varepsilon^p \tag{8}$$

where $e$ is the void ratio.

Elastic strains are induced by changes in net mean stress, deviatory stress and suction according to the expression

$$d\varepsilon^p = \frac{\kappa}{(1+e)}\frac{dp}{p} + \frac{1}{3G}dq + \frac{\kappa_s}{(1+e)}\frac{ds}{(s+p_{atm})} \tag{9}$$

where $G$ is the shear modulus, $\kappa_s$ is the elastic stiffness parameter against changes in suction and $p_{atm}$ is the atmospheric pressure.

### *2.2.2. Microstructural model*

The microstructural behavior is assumed to be elastic and volumetric. The microstructural volumetric strain depends on a microstructural effective stress ($\hat{p}$), defined by

$$\hat{p} = p + \chi s \tag{10}$$

where $\chi$ is a constant, defined by the slope of the neutral line.

Another assumption made in this formulation is the hydraulic equilibrium between microstructure and macrostructure. Therefore, only one suction variable should be considered.

In the ($p$, $s$) plane, a line corresponding to a constant microstructural effective stresses is called the neutral line (NL) because no microstructural strain occurs along it. The neutral line divides the ($p$, $s$) plane into two parts, defining the microstructural stress paths indicated in Fig. 1.

The increment of the microstructural elastic strain is expressed as a function of the increment of the microstructural effective stress:

$$\dot{\varepsilon}_{vm} = \frac{\dot{\hat{p}}}{K_m} = \frac{\dot{p}}{K_m} + \chi\frac{\dot{s}}{K_m} \tag{11}$$

In this equation, the subscript m refers to the microstructural level, the subscript $v$ refers to the volumetric component, and $K_m$ is the microstructural bulk modulus. We compute $K_m$ by the following law

$$K_m = \frac{e^{-\alpha_m \hat{p}}}{\beta_m} \tag{12}$$

### *2.2.3. Interactions between structural levels*

Microstructural effects induce irreversible macrostructural deformations, which are considered proportional to microstructural strain, as described by certain interaction functions.

Two interaction functions are defined: $f_c$ for microstructural compression paths and $f_s$ for microstructural swelling paths. For isotropic loading, the interaction functions depend on the ratio $p/p_0$.

The ratio $p/p_0$ indicates the degree of openness of the macrostructure relative to the applied stress state. When this ratio is low, it indicates a dense packing of the material, and it is expected that microstructural swelling induces large macrostructural plastic strains.

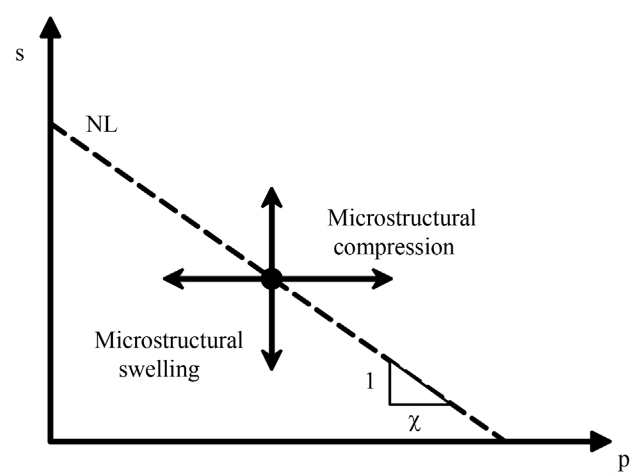


**Figure 1** - Definition of microstructural swelling and contraction paths.

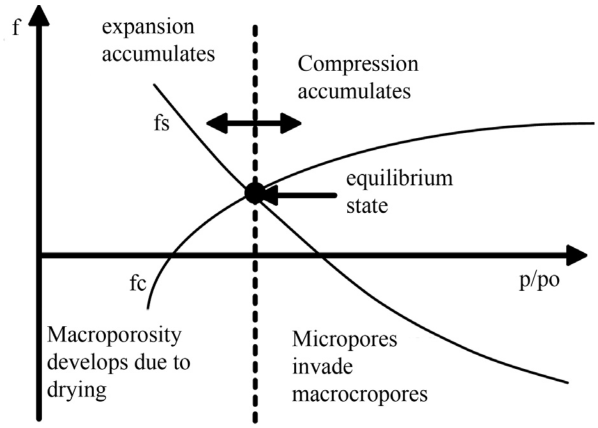


**Figure 2** - Interaction mechanisms between micropores and macropores.

According to Alonso *et al.* (1999) any suitable function for $f_s$ and $f_c$ that is consistent with the physical ideas presented in Fig. 2 can be adopted.

This paper adopted the interaction functions proposed by Alonso *et al.* (1999):

$$f_c = f_{c0} + f_{c1}\left(\frac{p}{p_0}\right)^{n_c} \tag{13}$$

$$f_s = f_{s0} + f_{s1}\left(1 - \frac{p}{p_0}\right)^{n_s} \tag{14}$$

## 3. Results and Analysis

The expansive soil of Petrolândia shows discrete variations in composition along its profile. Clay composes more than 54% of the soil, and sand represents less than 9%. The ratio of silt to clay decreases with depth, indicating that there is a translation of the thinner material from the surface to the sub-superficial horizons. The thinner material is carried by water and seepage through fissures. The soil has the following characteristics: $w_L$ = 60%, PI = 30%, $w_c$ = 19%, $w$ = 17.41% and $\gamma_d$ = 15.05 kN/m$^3$. The initial degree of saturation was 59.24%, which corresponds to a suction of 5.0 MPa.

The expansive soil matrix is characterized by a fine textured, compact, predominantly silicate clay permeated by micritic calcite crystals that comprise much of the silt and fine sand. Shaped lamellar particles were found, most likely originating from the filling of flattened channels and pores. These particles destroyed and compressed the soil matrix due to the action of the high activity clay (Ta) that occurs in this soil (Fig. 3a). Calcitic nodules are typical, and calcium carbonate ($CaCO_3$) commonly precipitates on the pore walls (Fig. 3b).

In the dry period, it has been observed that fissures in the soil surface have thicknesses that vary by only a few millimeters around a thickness of 120 mm. The thickness decreases with depth, and the extension reaches 2.0 m (observed in the inspection shaft). For water penetration, large fissures have a greater effect than a large number of narrow fissures because as the water content increases, the soil expands, and the slimmest fissures are progressively restricted, while the largest ones can remain open for a longer period of time. In the beginning of the wetting process, the fissure intensity is as important as the width and depth of the individual fissures. As rain occurs, the soil absorbs water from the surface and from the interior of the fissures, and the clay particles expand as micro-reliefs appear. The surface is composed of blocks of soils of irregular shapes, which are detected in an area of 100 m$^2$ chosen randomly in the field. The area represents approximately 190 blocks, each with an average area of 0.53 m$^2$ (Fig. 4a). It has also been observed that rain is sufficient to make some superficial fissures disappear completely (Fig. 4b). In this soil, free calcium carbonate predominated over sodium (Ferreira, 1995), thus presenting

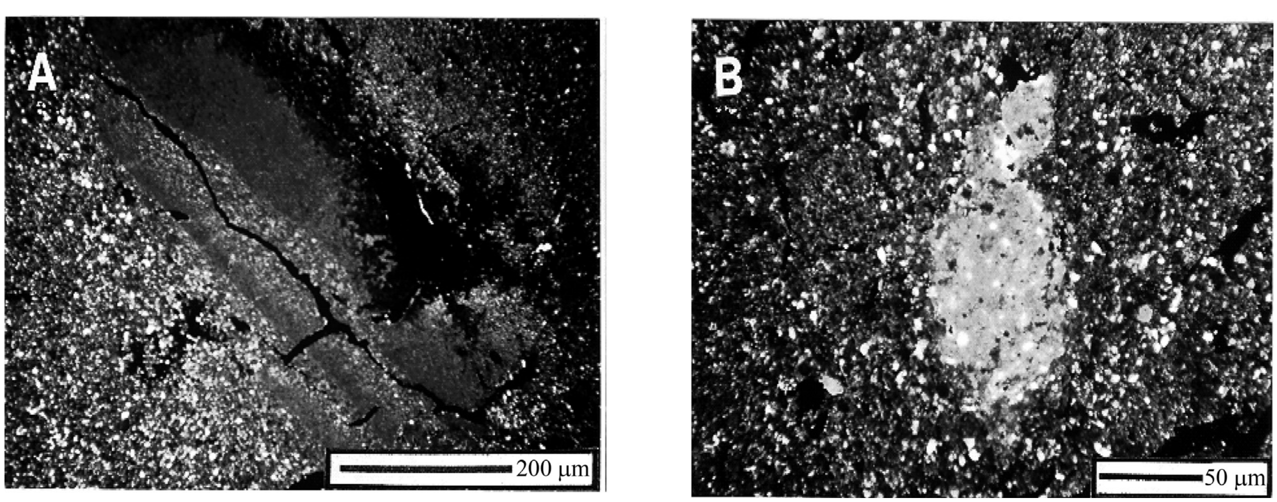


**Figure 3** - a) Micrograph of fractures and flattened pores. b) Micrograph of calcitic nodule.

a smaller number of cracks with increased bandwidth, confirming the observations of Ahmad (1983).

The soil water content, measured from the surface to a depth of 3.50 m, changes in the rainy period from 42% to 20.90%, and in the dry period it changes from 14.54% to 21.03% (Fig. 4c). Beyond a depth of 2.50 m, no significant variation in water content between the dry and rainy periods was observed during the two years of observation, which indicates that this is the active zone of change in water content.

The soil swelling pressure obtained by the constant volume method increases with depth in the rainy period, and in the dry period it decreases until a depth of 2.5 m; from this depth onward it remains basically constant (Fig. 4d). In the same way, swelling pressure and effective stress have been found to vary with depth (Fig. 4e). Up to 2.5 m depth, there is considerable influence of the climatic conditions on water content, swelling pressure and fissure depth. In the field, fissures were observed at up to 2.0 m depth, in the dry period.

The volume change that occurs due to inundation was analyzed by considering the influence of vertical stress at inundation, along with the swelling pressure, the initial water content and the drying that occurred under stress.

### 3.1. Influence of consolidation vertical stress

Strain was plotted as a function of time after inundation in simple oedometer tests, as shown in Fig. 5. Expansion and collapse can sometimes occur simultaneously. Therefore, what is measured is the net deformation, which is a function of vertical stress, void ratio and water content (state of stress) in the soil before it is inundated. At some pre-determined state of stress, the deformation due to inundation is equal to expansion due to stress at 160 kPa, or expansion and collapse in the range of 240 to 400 kPa (initially, the soil compresses for 8 min, then it expands until 240 min and compresses until deformations stabilize). Collapse is caused at stress greater than 640 kPa.

The deformation process of expansion or collapse caused by inundation can be divided into three phases:

i) Initial - From time zero to one minute, in which small deformations are observed and the water only moistens the periphery.

ii) Primary - From 1 minute to 300 min, the water percolates from the periphery to the center, moistening the soil progressively (as a function of hydraulic conductivity). Deformations occur with higher intensity.

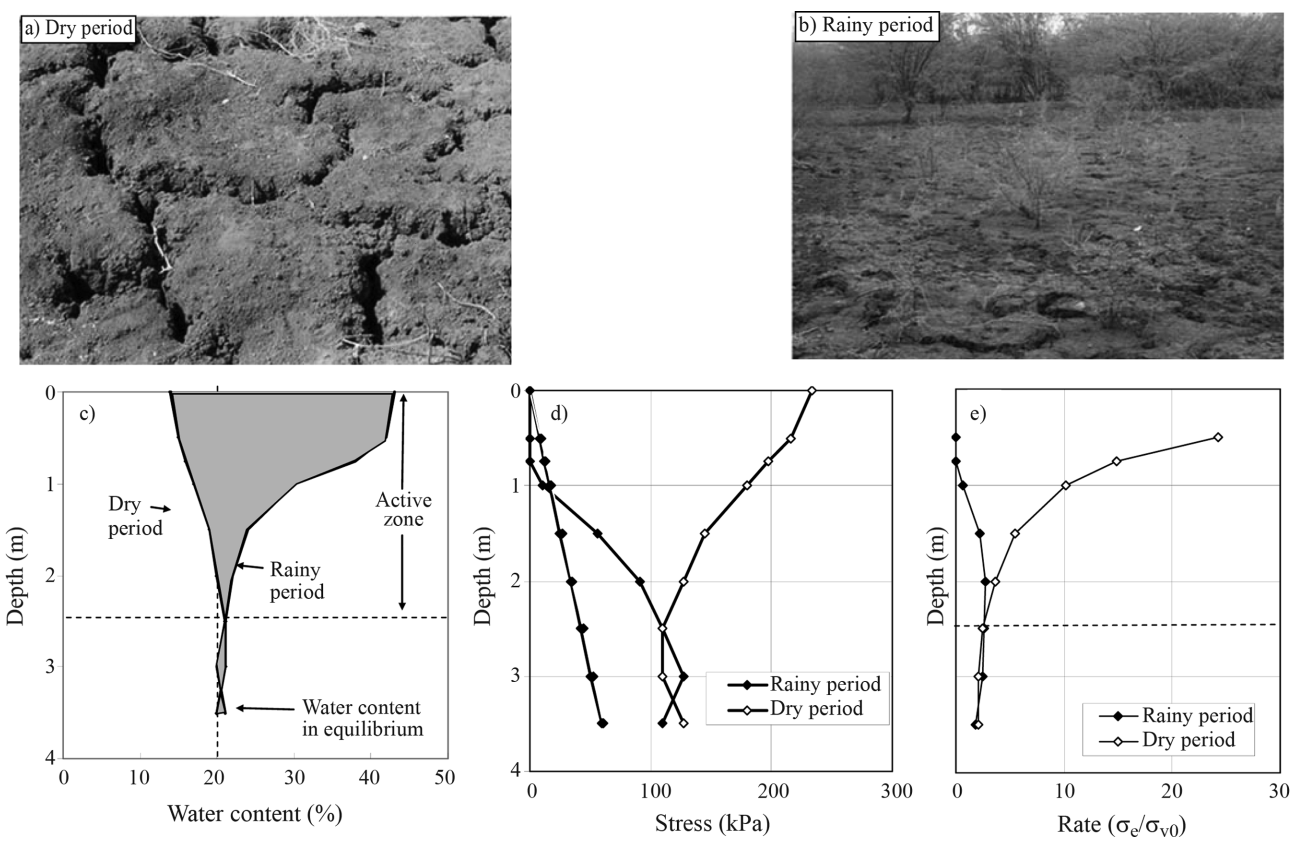


**Figure 4** - a) Fissures and micro-reliefs in the dry period. b) Fissures and micro-reliefs in the rainy period, c) Active zone. d) In situ stress and expansion stress. e) Ratio between in situ stress and expansion stress in an expansive soil from Petrolândia.

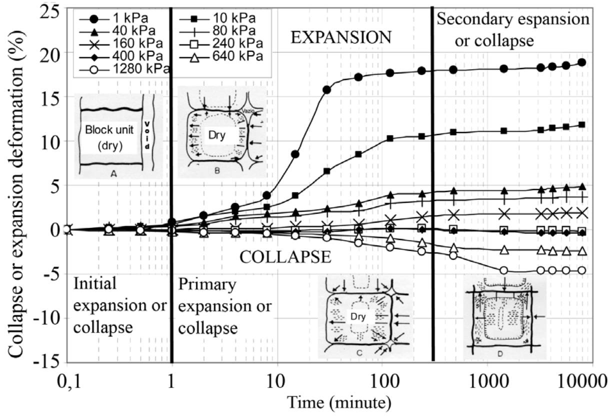


**Figure 5** - Deformation as a function of time during the advance of the wetting front. (a) Small alteration in the soil water content; (b) Change in water content of the soil periphery; (c) Only the central nucleus maintains the initial water content; (d) Change in the water content of the whole soil.

iii) Secondary - Beyond 300 minutes, the water moistens the central nucleus, and the empty spaces are almost completely filled with water. The deformation velocity decreases (Fig. 5). Roo (2006) suggests that the initial deformations are associated with the microstructure, whereas the primary and secondary deformations are associated with the macrostructure.

The variation of expansion or collapse potential, as a function of consolidation vertical stress, void ratio or degree of saturation before soil inundation, is shown in Fig. 6.

For stresses lower than 312 kPa (Fig. 6a), void ratios higher than 0.745 (Fig. 6b) and saturation degrees less than 63.90% (Fig. 6c), Petrolândia soil expands when there is an increase in soil water content, characterizing the expansion region. For stresses greater than 312 kPa (Fig. 6a), void ratios less than 0.745 (Fig. 6b) and saturation degrees greater than 63.90% (Fig. 6c), Petrolândia soil collapses when water content increases, characterizing the collapse region. There are values of stress ($\sigma_{crit}$ = 312 kPa), void ratio ($e_{crit}$ = 0.745) and degree of saturation ($Sr_{crit}$ = 63.90%) that are critical. At these values, the soil volume does not change when inundated (Fig. 6).

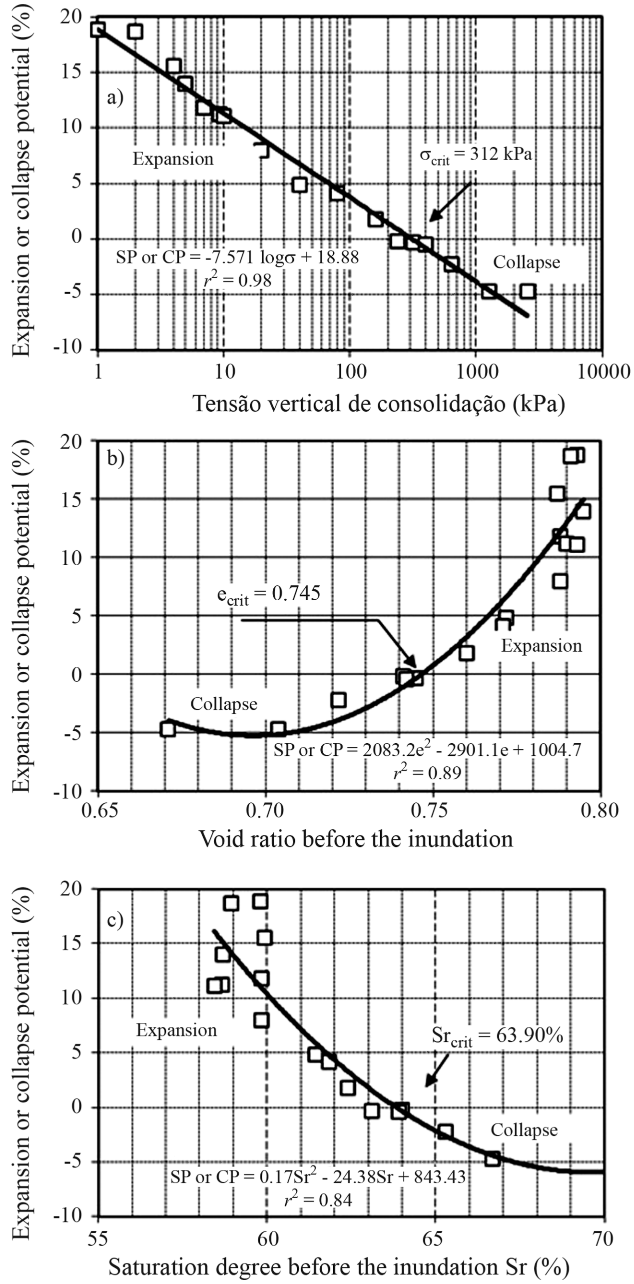


**Figure 6** - Difference between expansion potential and collapse potential measured in simple oedometer tests. a) with consolidation vertical stress; b) with void ratio before inundation; c) with saturation degree before inundation.

## 3.2. Influence of initial water content

The "free" expansion variation increases (approximately linearly) with the decrease in initial water content (increasing suction) and with the decrease in vertical stress of consolidation before inundation (Fig. 7a).

The "free" expansion of the expansive soil under study, at a water content of 17.41%, has high expansivity according to the Vijayvergiya & Ghazzaly (1973) criteria, which assume a consolidation stress of 10 kPa.

The values of swelling pressure and physical indices for samples that were previously wetted or dried before being inundated were determined by the loading methods after expansion, after consolidation and expansion under vertical stress (Method 1) and after collapse under stress (Method 2) with initial water contents of 22.58%, 20.80%, 17.41% and 7.76% (Table 1). The highest expansion stress values were obtained at the lowest water content values (7.76%), saturation degree values (35.22%) and void ratio values (0.57), and at higher suction values (117 MPa) and higher dry apparent specific weights (16.96 kN/m$^3$). The previous wetting process of the soil causes reduction in swelling pressure, whereas desiccation causes an increase.

This shows that, in the field, the climate conditioning factors have considerable influence on soil expansion stress.

The specific volumetric deformation curves that are observed under soil consolidation vertical stress ($\varepsilon_v$ *vs.* $\sigma$ - log) at different initial water content levels, and under stresses of 10 kPa and 160 kPa, are presented in Fig. 7b. At the same initial water content, the expansion due to inundation decreases with increasing consolidation vertical stress.

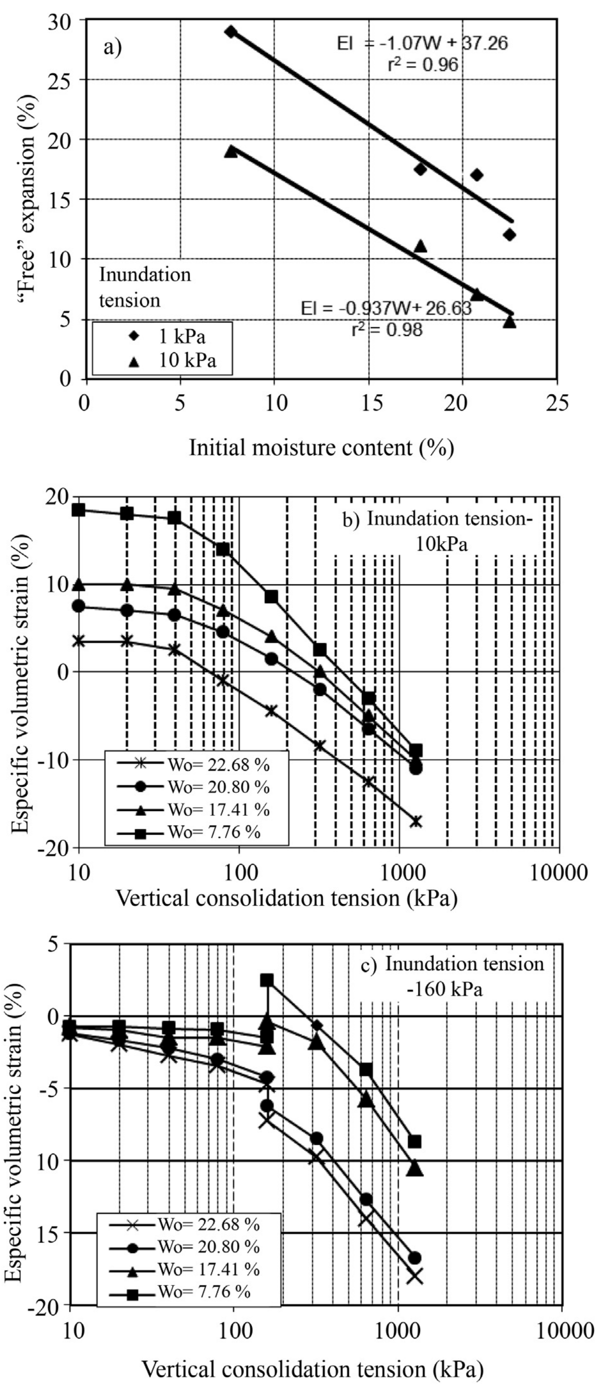


**Figure 7** - Influence of initial water content: a) in "free" expansion; b) in compression; c) in expansion or collapse under stress.

At the same level of consolidation vertical stress, soil expansion is reduced as initial water content increases (Fig. 7b) because the previous wetting causes expansion before loading. Under a consolidation vertical stress of 160 kPa, soil inundation causes collapse at initial water content of 22.58% or 20.80%, and expansion at initial water content of 17.41% or 7.76% (Fig. 7c). A similar behavior was observed by Presa (1982) in soil with approximately the same void ratio and different initial water content, which was consolidated under a stress of 200 kPa. The initial water content and stress greatly affect the volume change observed when the soil is inundated.

### 3.3. Drying

The process of soil deformation due to desiccation is much slower than deformation during wetting. This is due to the way the water is transferred. During inundation, it is processed in the liquid phase, but in desiccation it is partially processed in the vapor phase.

The effect of desiccation on the total deformation of the soil is greater at lower stress than at higher stress (Fig. 8a). The deformations measured during desiccation result from the addition of three components: immediate compression, deformation due to vertical stress and retrac-

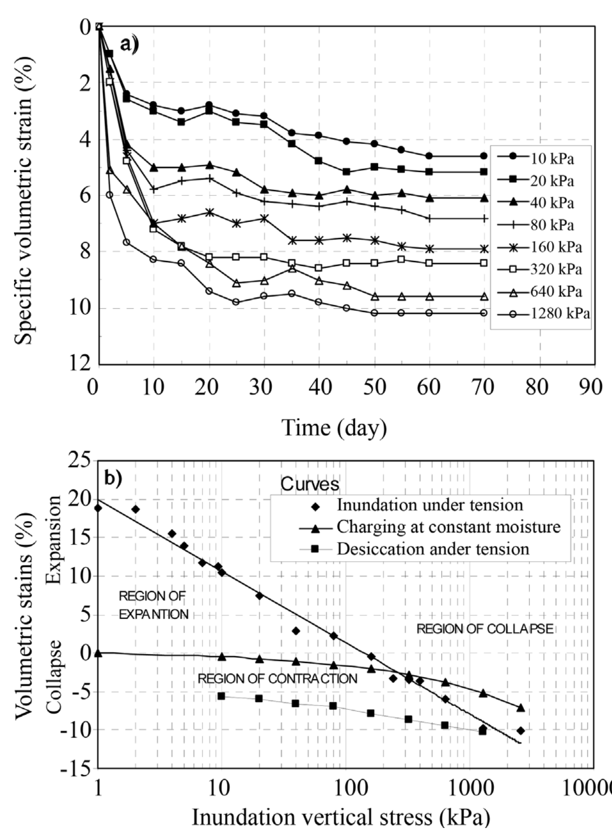


**Figure 8** - Volumetric deformation with the addition of stress, desiccation and inundation: a) volumetric deformation with the simultaneous addition of stress and desiccation; b) expansion, collapse and contraction regions.

**Table 1** - Influence of initial water content in deformation and stress of expansion.

| W (%) | Initial suction (kPa) | $e_o$ | $\rho_d$ (kN/m$^3$) | Sr (%) | Relationship of expansion deformation and stress | | Expansion stress (kPa) | |
|---|---|---|---|---|---|---|---|---|
| | | | | | εs (%) | σ (kPa) | Method 1 | Method 2 |
| 7.76 | 117.000 | 0.597 | 16.96 | 35.22 | εs = -11.82 logσ + 29.73 | $r^2$ = 0.99 | 456 | 328 |
| 17.41 | 5.000 | 0.801 | 15.05 | 59.24 | εs = -7.84 logσ + 18.66 | $r^2$ = 0.99 | 333 | 239 |
| 20.70 | 700 | 0.885 | 14.37 | 63.39 | εs = -8.62 logσ + 16.64 | $r^2$ = 0.99 | 153 | 83 |
| 22.60 | 200 | 0.936 | 14.00 | 65.43 | εs = -6.36 logσ + 11.60 | $r^2$ = 099 | 85 | 67 |

W - initial water content in the dry period; $e_o$ - void ratio; Sr - degree of saturation of water; εs - expansion deformation (εs = 100 $\Delta H/H_i$, where $\Delta H$ is the body's height variation due to inundation, and $H_i$ is the specimen's height before inundation); σ - stress; ρd- dry apparent specific weight; $r^2$ - correlation coefficient; Method 1 - loading after expansion with different consolidation vertical stress; Method 2 - expansion and collapse under stress.

tion. At stresses less than 40 kPa, the time required for 50% of deformations to occur is at least 8 days, but for stresses greater than 320 kPa it is at most 2 days. This is explained by the fact that, at consolidation stresses less than 40 kPa, the immediate compressions and the compressions due to the stress effect are reduced with time compared to the ones caused by desiccation, and they prevail over the compressions caused by retraction, which are slower. At stresses greater than 320 kPa, the immediate compressions and the ones due to the stress magnitude effect have greater importance and occur more quickly than the compressions caused by desiccation. The region between the loading curves, with constant water content, and the curves of desiccation under stress limit the contraction. (Fig. 8b).

The curves describing volume changes due to changes in water content under stress and those describing volume changes due to loading at constant water content define two regions: a region of expansion at stress lower than 277 kPa and a region of collapse at stress greater than 277 kPa (Fig. 8b). The area formed by the curves describing volume variation due to water content change under stress, volume change due to loading at constant water content and desiccation under stress constitutes an important piece of information about the influence of the stress path on the behavior of volume variation due to change in soil water content. These curves define the limits of the regions of expansion, collapse and contraction.

### 3.4. Numerical simulation

Three suction-controlled oedometric tests involving inundation at different stress levels were conducted. In the first simulation, the specimen was flooded at 10 kPa. In the second test, the inundation occurred at 160 kPa. In the third test, the sample was inundated under a vertical pressure of 640 kPa. Laboratory results are presented in Fig. 9.

The model described above was implemented in the Finite Element program CODE_BRIGHT (Olivella *et al.*, 1996; Sanchez *et al.*, 2005), which was used to simulate the suction-controlled oedometric tests.

The parameters used in the simulation were obtained from tests results and are listed in Table 2.

Laboratory data and numerical simulation results are presented in Fig. 9.

In Test 1, the sample was flooded under low vertical stress (10 kPa), and swelling deformation was measured. A volumetric strain of 10% was registered. In Test 2, inundation occurred under a higher vertical stress (160 kPa), and the swelling volumetric strain was lower (approximately 2%). For Test 3, inundation occurred when the vertical stress was 640 kPa. At this stress level, the sample collapses.

The simulation results show very good agreement with the experimental data. The loading observed under controlled suction and the swelling observed as a result of suction reduction under a determined level of vertical stress were reproduced very well. The collapse at higher stress levels was also in agreement with experimental results.

Simulation results also allow us to analyze the volume change behavior of microstructural and macrostructural levels separately, as illustrated for void ratio variation in Fig. 10.

According to the constitutive model used, a decrease in suction implies a microstructural swelling (Fig. 1), which was observed in the three tests (Fig. 10).

**Table 2** - Parameters used in simulation.

| |
|---|
| Parameters defining BBM for the macrostructural level |
| $\kappa = 0.009$ $\kappa_s = 0.002$ $\lambda(0) = 0.10$ $r = 0.50$ $\beta$ (MPa$^{-1}$) = 1.0 |
| $p_0$*(MPa) = 0.22 $p^c$ (MPa) = 0.10 |
| Parameters defining the laws for the microstructural level |
| $\chi = 1.0$ $\alpha_m$ (MPa$^{-1}$) = 0.006 $\beta_m$ (MPa$^{-1}$) = 0.012 |
| Interaction functions |
| $f_{c0} = -0.10$ $f_{c1} = 1.5$ $n_c = 0.50$ $f_{s0} = -1.50$ $f_{s1} = 3.70$ $n_s = 2.0$ |
| $e_{macro} = 0.80$ $e_{micro} = 0.30$ |

Changes in the microstructural void ratio are not greatly influenced by the stress level, whereas the macrostructural void ratio is greatly affected by stress.

In Test 1, when inundation occurs under a vertical stress of 10 kPa, both the microstructure and macrostructure expand. The BBM model can reproduce some of the expansion at low stress levels. Moreover, the ratio $p/p_0$ is low, and the $f_s$ interaction value is positive. The induced microstructural strains are due to expansion.

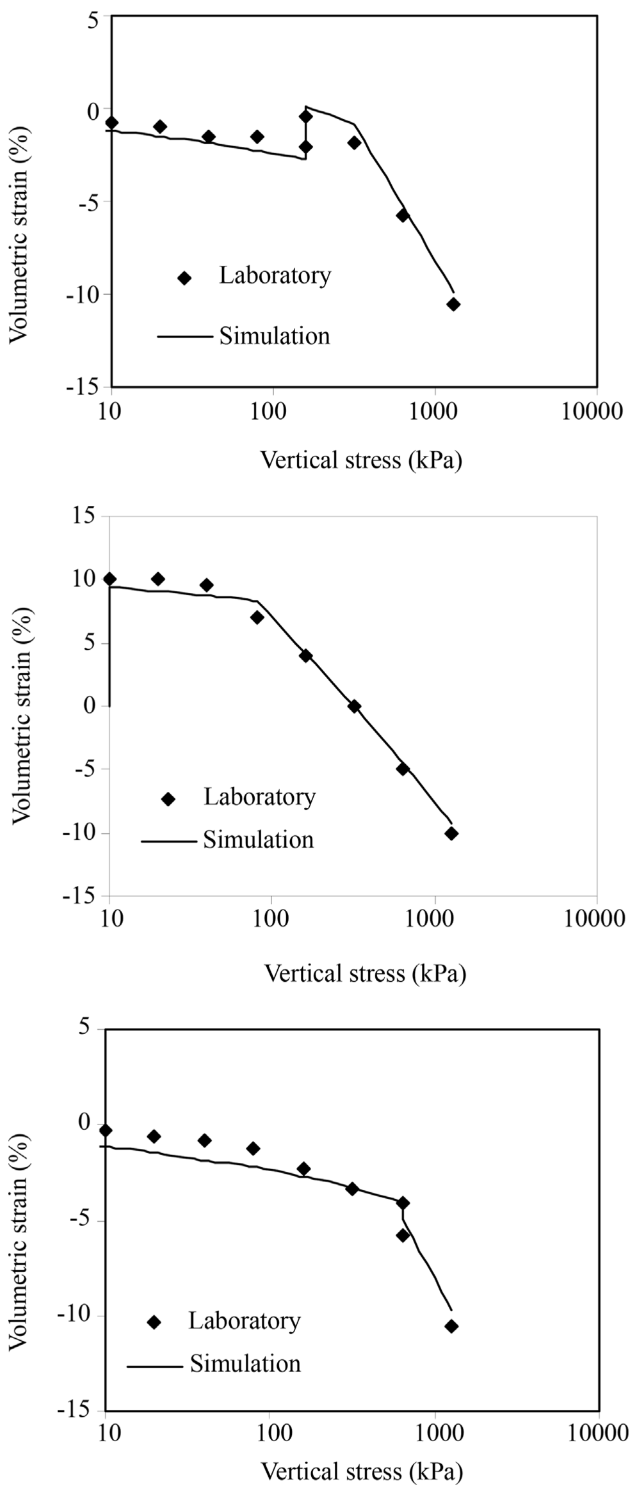


**Figure 9** - Comparison between laboratory data and simulation results for Tests 1, 2 and 3.

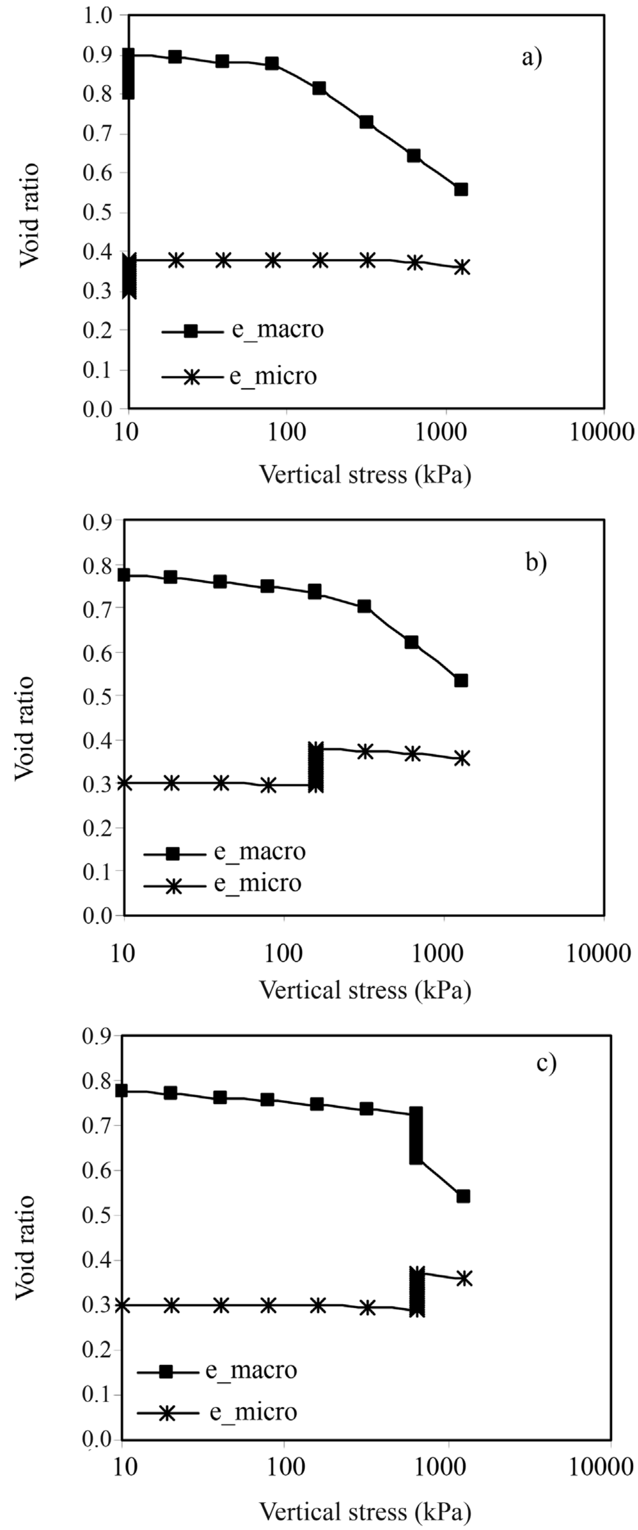


**Figure 10** - Simulation results of macro and micro void ratio variation for a) Test 1; b) Test 2; c) Test 3.

As the inundation stress level increases to 160 kPa (Test 2), expansion is observed only in the microstructure. Because the ratio $p/p_0$ is greater than in Test 1, the $f_s$ interaction value decreases, and the induced macrostructural strains of expansion are smaller.

When the sample is inundated at a higher stress level, such as in Test 3, the macrostructure collapses. The influence of microstructural strain is minimal.

## 4. Conclusions

We conclude that soils with lower initial water content and higher exterior applied vertical stress exhibit greater expansion due to their increased water content.

The order in which the soil is subjected to stress or inundation affects the expansion stress value. The inundation leads to soil volume increase (expansion) or decrease (collapse) depending on the initial moisture and the vertical stress applied to the soil.

The numerical results demonstrate that the double structure generalized plasticity model proposed by Sanchez *et al.* (2005) is able to reproduce the experimental behavior of expansive soils.

Finally, the factors that limit the regions of expansion, collapse and contraction are the curves of inundation, the changing or constant humidity and the desiccation under stress.

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