International Conference on Case Histories in Geotechnical Engineering

(2008) - Sixth International Conference on Case Histories in Geotechnical Engineering

14 Aug 2008, 2:15pm - 4:00pm

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Recommended Citation

Nowamooz, H. and Masrouri, F., "Swelling Soils Behaviour in Cyclic Suction-Controlled Drying and Wetting" (2008). *International Conference on Case Histories in Geotechnical Engineering*. 44.
https://scholarsmine.mst.edu/icchge/6icchge/session07/44

SWELLING SOILS BEHAVIOUR IN CYCLIC SUCTION-CONTROLLED DRYING AND WETTING

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ABSTRACT

Cyclic drying and wetting phenomena of the expansive clayey soils cause the progressive settlements which could affect principally the foundations of buildings, the drainage channels and the buffers in radioactive waste disposals. In order to better understand the coupling between these hydraulic cycles and the mechanical behaviour of the swelling soils, this article presents an experimental study performed on two different expansive soils (molded and natural) using oedometer tests by imposing suction variations with the osmotic technique. Several successive swelling and shrinking cycles were applied under different constant vertical net stresses. During the suction cycles, the compacted samples showed cumulative shrinkage strains. On the other hand, the natural samples presented cumulative swelling strains. At the end of the suction cycles, the volumetric strains reached an equilibrium stage which indicates an elastic behaviour of the samples. We can relate these elastic behaviours to the soil fabric and especially to the microstructural content of soil.

INTRODUCTION

The clayey soils are widely used in geotechnical engineering for dam cores or to build barriers in waste landfill. These types of materials are also considered for engineered barriers in nuclear waste storage facilities. On site, they can be submitted to complex hydraulical/mechanical solicitation that could change dramatically their coupled hydromechanical behaviour.

In this context, the swelling materials were the subject of many studies, particularly to determine the strong dependence of their compressibility to the applied suction (Push 1982; Gens and Alonso 1992; Romero *et al.* 1999; Cui *et al.* 2002; Cuisinier 2002). The majority of these experimental results were deduced from the tests implying only a simple hydraulic (drying or wetting) path followed by a mechanical loading. However, different authors (Tessier 1984; Osipov *et al.* 1987; Dif and Bluemel 1991; Day 1994; Al-Homoud *et al.* 1995; Basma *et al.* 1996) without employing the suction imposition techniques showed that the successive wetting and drying cycles induced the irreversible shrinkage or swelling accumulation as well as the significant changes in the soil fabric of the studied swelling soils. The same cyclic tests carried out with the controlled suction devices by Chu & Mou (1973), Alonso *et al.* (1995) and Alonso *et al.* (2005) allowed to underline the influence of the vertical applied stress during the wetting and drying cycles on the swelling soils. All these authors implied that an equilibrium elastic state can be reached at the end of several cycles.

These researches made it possible to highlight the role of the soil fabric: micro- and macrostructure on their mechanical behaviour, which led to develop an elastoplastic model for the swelling soils (Alonso *et al.* 1999). Although this model takes into account the accumulation of strains during the wetting and drying cycles, but the basic characteristics of the equilibrium state is not still well-known. The following questions can be stated:

- whether this equilibrium state is dependent or independent on the initial state of soil,
- whether the soil presents a final fatigue at its equilibrium stage and its behaviour remains completely elastics, or whether there will be an opposite effect for the additional suction cycles after reaching the equilibrium point,

In order to find out an appropriate response for these questions, this paper presents an experimental study performed on two swelling soils using oedometer tests by imposing the suction variations with the osmotic technique. Several successive swelling and shrinkage cycles were applied under different values of constant vertical net stress. During the wetting and drying cycle, both soil followed the same stress paths.

OSMOTIC TECHNIQUE

The study of the hydromechanical behaviour of the silt-bentonite mixture used in this article requires experimental devices to impose a suction range between zero and several MPa. In order to achieve this goal, the osmotic method was selected. The principle of this method is to put in contact a soil sample and a solution of macromolecules (polyethylene glycol, PEG) with a semi-permeable membrane between them (Zur, 1966). This membrane prevents the solution macromolecules to move towards the sample but it allows water exchange. Water movements, and thus suction variations, are controlled by the osmosis phenomenon: The higher the concentration of the solution, the higher the imposed suction. The relation between the imposed suction and the concentration was characterized and justified by various authors (Williams and Shaykewich 1969; Delage et al. 1998; Cuisinier and Masrouri 2005). Cui (1993) has proposed an empirical calibration relationship between PEG concentration and suction:

$$s=11c^2 \qquad (1)$$

where c is the concentration and s is the imposed suction. The molecular weight of PEG chosen for these tests is 6 000 which makes it possible to impose a maximum suction of 8.5 MPa. A suction-controlled oedometer device using osmotic solutions proposed by Kassif and Ben Shalom (1971) and modified by Delage et al. (1992) was used to perform the loading/unloading mechanical cycles.

TESTED MATERIALS

The study was initially conducted on an artificially prepared mixture 40% of silt and 60% of bentonite. The mineralogical composition of the compacted material was determined by X-ray diffraction. The silt contains 60% quartz, 20% montmorillonite, 11% feldspar, and the remaining part was made up of kaolinite and mica. The bentonite is composed of more than 90% of calcium montmorillonite. The size of the particles used to prepare the samples was less than 400 µm (obtained by sieving). The initial water content and the initial dry density of the compacted soil are respectively about, 15 % and 1.27 Mg/m^3 under a vertical pressure of 1 000 kPa.

Secondly, we studied a natural soil located on the experimental site of Mignaloux-Beauvoir region, in proximity of Le Deffend, about 4 km south-east of Poitiers (France). An in-situ coring was performed to the depth of 7 meters for geological and geotechnical investigations within the framework of ANR ARGIC project (Vincent *et al.* 2006). The studied clayey layer is located between 5.20 m and 5.70 m of depth. The dry density of the clayey soil varies between 1.75 and 1.80 Mg/m^3 and its water content is about 15 %. The mineralogical composition of the natural soil determined by X-ray diffraction shows that the smectite minerals are dominant.

The geotechnical characteristics of both clayey materials are presented in Table 1. The liquid limit and the plasticity index confirm the high swelling capacity of both soils. The initial matric suction, measured by the filter paper method (ASTM 1995a), was comprised between 20 and 25 MPa for both materials. The swelling properties of the soils were determined by the free swelling method (ASTM 1995b): the swelling potential defined as the ratio of ($\Delta h/h_0$) where Δh is the height increase and h_0 is the initial height when the sample is fully saturated and the swelling pressure defined as the pressure required to eliminate height variations produced by saturation. The swelling pressure and swelling potential values are also presented in Table 1 for the compacted and natural soil. The denser natural soil presents the higher swelling potential as well as the higher swelling pressure.

Table 1 - Properties of the soils used in this study

Soil	Liquid limit (%)	Plasticity index (%)	Specific gravity (G_s)	Swelling potential (%)	Swelling pressure (kPa)
Compacted mixture	87	22	2.67	17	150
Natural material	65	25	2.62	24	2 200

Mercury intrusion porosimetry (MIP) tests were carried out to evaluate the pore size distribution of the studied materials (Fig. 1). One of the fundamental characteristic of the clayey materials is their two distinct structural levels: micro- and macrostructure (Alonso 1987). The pore size distribution confirm this fact for the compacted soil, where the dominant diameters are respectively 0.011 µm which would correspond to the pores inside clay aggregates (microstructure) and a larger pore of 7.5 µm which would correspond to the macrostructure.

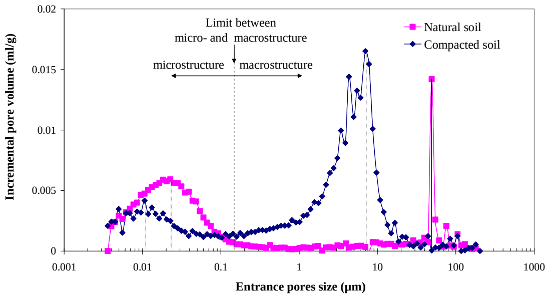


Fig. 1 - Pore size density function evaluated from MIP results

The boundary between two pore sizes is about 0.150 µm since the pores of this magnitude are not affected by the magnitude of the mercury intrusion pressure (Fig. 1). According to Jurin-Laplace law ($s = \dfrac{2\sigma\cos\theta}{r}$ where the interfacial tension σ and the contact angle θ are 0.073 N.m^{-1} and 0° for water, r (µm) is the pore raduis and s (MPa) is the suction), this pore diameter (0.150 µm) corresponds to a suction of about 2.5 MPa considered as the suction limit between micro- and macrostructure. On the other hand, the natural soil presents only a dominant microstructure with the maximal pore size value of 0.022 µm.

APPLIED STRESS PATHS

In this part, the influence of the suction cycles on the behaviour of both swelling soils will be studied. In order to analyse the mechanical behaviour of these soils for the followed stress paths, it is essential to apply a minimum number of suction cycles. The low permeability of clayey material requires a long period to reach the equilibrium state. The applied suction cycles by osmotic method took at least two or three months for the studied swelling soils. This period let us perform only three wetting and drying cycles.

For all the performed tests on the compacted soil (C1, C2 and C3 tests) and on the natural soil (N1, N2 and N3 tests), the initial state is represented by the point A in figure 2 which corresponds to the samples once inserted in the oedometers with initial suction of 20 MPa for both materials. The initial height of the samples is 10 ± 0.5 mm and their diameter is 70 mm in the oedometers. In the logarithmic representation planes, zero suction is replaced by 0.01 MPa.

At the beginning, the initial suction of 20 MPa was decreased to 8 MPa under the initial vertical stress of 10 kPa (A-B). Three different vertical stresses were then applied: 15 kPa (point C_1) for C1 & N1 tests, 30 kPa (point D_1) for C2 & N2 tests and 60 kPa (point E_1) for C3 & N3 tests. Then, three successive wetting and drying cycles with a suction range between 0 and 8 MPa were applied. These low stresses were selected to visualize the plastic strains only due to the suction cycles but not due to the loading phase. As the first drying and wetting cycle affects more highly the soils behaviour regarding to the successive cycles, the suction from 8 to 0 MPa was decreased in two steps with an intermediate suction: 2 MPa for the compacted soil (Points M, I , O) and 3 MPa for the natural soil (Points M', I', O'). These suctions were selected close to the suction limit between micro- and macrostructure. The followed stress paths of all the performed tests are reported for the compacted soil in Table 2 and for the natural soil in Table 3.

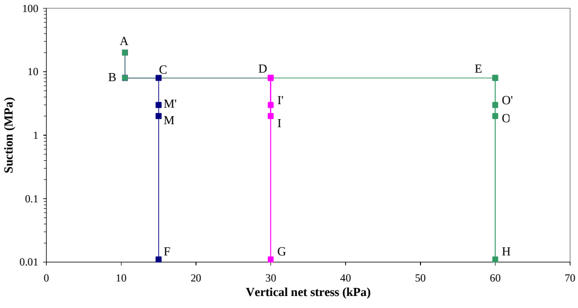


Fig. 2. Description of (σ_v-s) plane

Table 2. Description of the followed stress paths for the compacted soil

C1	A-B-C_1-M_1-F_1-M_2-C_2-F_2-C_3-F_3-C_4
C2	A-B-D_1-I_1-G_1-I_2-D_2-G_2-D_3-G_3-D_4
C3	A-B-E_1-O_1-H_1-O_2-E_2-H_2-E_3-H_3-E_4

Table 3. Description of the followed stress paths for the natural soil

N1	A-B-C_1-M'_1-F_1-M'_2-C_2-F_2-C_3-F_3-C_4
N2	A-B-D_1- I'_1-G_1-I'_2-D_2-G_2-D_3-G_3-D_4
N3	A-B-E_1-O'_1-H_1-O'_2-E_2-H_2-E_3-H_3-E_4

WETTING AND DRYING RESULTS

The variation of void ratio versus suction for the three cyclic tests (C1, C2 and C3) is presented in Fig. 3. The first wetting path (A-B) produces an expansion for each sample. The compacted samples present a shrinkage accumulation during the following successive cycles. The stress intensity influences the amount of shrinkage accumulation especially at the end of the first wetting and drying cycle: the higher the applied stress, the higher the shrinkage accumulation. At the end of suction cycles, the volumetric strains tend towards an equilibrium stage and the samples present a completely reversible behaviour. This convergence completely reached for the C1 and C2 tests of the compacted soil. However this final elastic stage may be reached for sample C3 with one or two additional cycles.

For the C1 test, the soil presents even a small swelling accumulation during its last wetting and drying cycle (C_3-F_3-C_4) after reaching the equilibrium state (Fig. 3). It can be supposed that there will be an opposite effect for the additional suction cycles after reaching the equilibrium point. Although there are not a lot of experimental results in our study to confirm this phenomenon; but in reality the clayey soil produced its principal damage of course during an important hydraulic solicitation and especially after several humid and dry periods which indicates that the swelling soils never presents a sign of fatigue or equilibrium stage after this long time.

As it was mentioned and we can observe in Fig. 3, the first wetting/drying cycle produces the highest shrinkage accumulation increasing accordingly with the applied stresses. Fig. 4 shows the variation of void ratio for the first wetting and drying cycle with the intermediate suction of 2 MPa for all the compacted samples. The plastic shrinkage accumulation is produced for the suction range between 0 and 2 MPa applied to the macrostructure. We can consider that the microstructure produces the elastic strains for the suctions between 2 and 8 MPa as the slope of suction variation in this range during the drying and wetting path: (C-M) path for test C1, (D-I) path for test C2 and (E-O) path for test C3 is the same while it decreases with the applied stress.

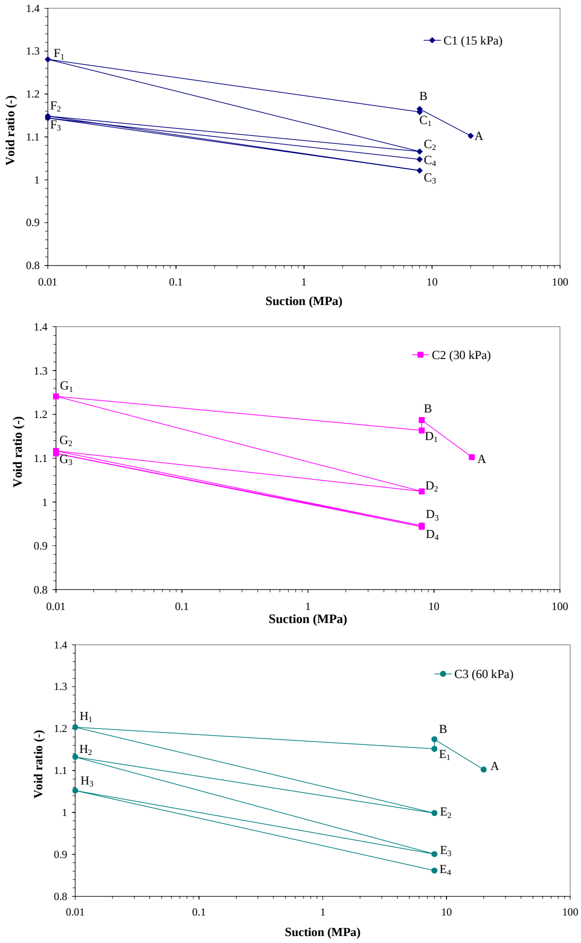


Fig. 3 – Variation of void ratio versus suction in cyclic controlled-suction paths for the compacted soil (C1, C2 and C3 tests)

The (e-log s) plane is presented in Fig. 5 for the three cyclic tests (N1, N2 and N3) carried on the natural soil. The path (A-B) also produces an expansion for all the samples. On the other hand, the samples show a swelling accumulation during the following successive cycles. The stress intensity decreases the amount of swell accumulation. The convergence to the equilibrium stage is not completely reached at the end of wetting and drying cycles for all the three performed tests. It seems that we need more additional suction cycles for the applied stresses to obtain this reversible state.

The swelling accumulation during the first wetting and drying cycle is presented in Fig. 6 with the intermediate suction of 3 MPa for all the performed tests on the natural soil. We can consider that the slope of suction variation between 3 and 8 MPa: (C-M') for test N1, (D-I') for test N2 and (E-O') for test N3 is the same during the drying and wetting path. In other words, we can state the microstructure presents an elastic behaviour. However, this slope seems not to be modified by the applied stresses for the natural soil. The plastic swelling accumulation is produced for the suction range between 0 and 3 MPa applied to the macrostructure.

As the followed stress paths were maintained the same for both soil, we can state that the denser soil produces the swelling accumulation while the looser one shows the shrinkage accumulation during the wetting/drying cycles. Here we can even predict that if the studied silt/bentonite mixture was very heavily compacted, we can expect the swelling strain accumulation during the suction cycles.

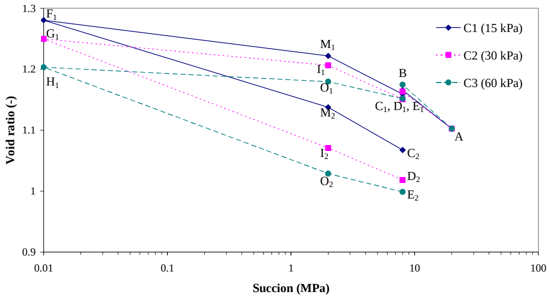
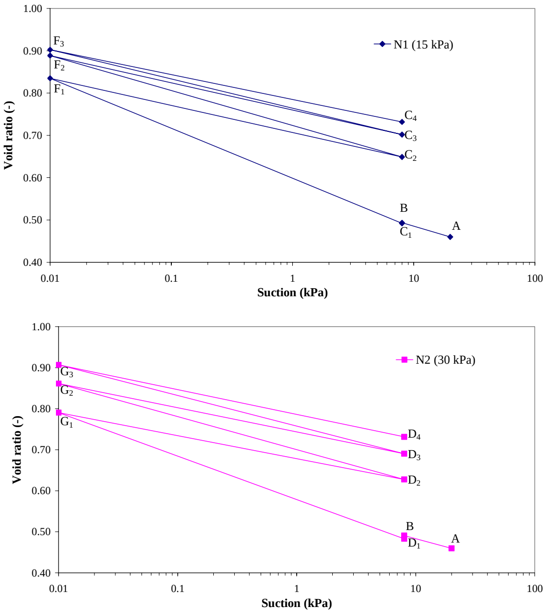


Fig. 4 – Variation of void ratio during the first wetting and drying for the compacted soil



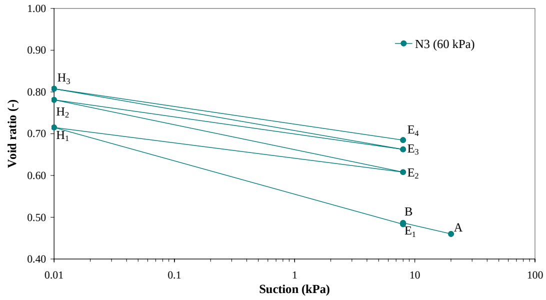


Fig. 5 - Variation of void ratio in cyclic controlled-suction paths for the natural soil (N1, N2 and N3 tests)

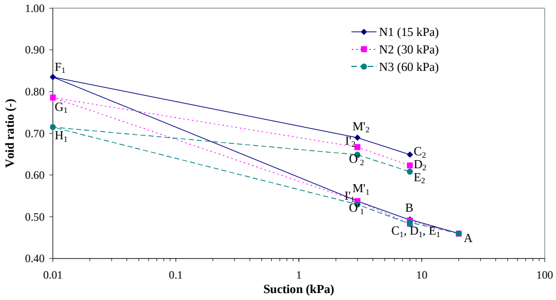


Fig. 6 – Variation of void ratio during the first wetting and drying for the natural soil

The suction limit between two micro- and macrostructural levels was initially considered about 2.5 MPa. As the soil behaviour is completely reversible after several successive suction cycles between 0 and 8 MPa, we could consider that this suction limit has been increased to 8 MPa at the equilibrium state. The slope of the last suction path in the (e-log s) plane in Figures 4 and 6 can be considered as the elastic index of the equilibrium stage ($\kappa_m = \Delta e / \Delta \ln s$). Fig. 7 presents this elastic index during the last applied suction cycle for both studied materials at different vertical stresses.

We can relate this elastic index variation to the soil fabric and especially to the microstructural content of soil. The elastic index decreases significantly with applied stress for the natural soil presenting a dominant microstructure. While it increases slightly for compacted samples with a macrostrucrtural soil fabrics. Consequently, we can indicate that κ_m value depends on the void ratio of the microstructure (e_m). It can be also concluded that the applied vertical stresses modify significantly the microstructural void ratio of the natural soil. The variation of e_m value can be neglected for the compacted soil and so the mechanical loading is only applied on the macrostructure.

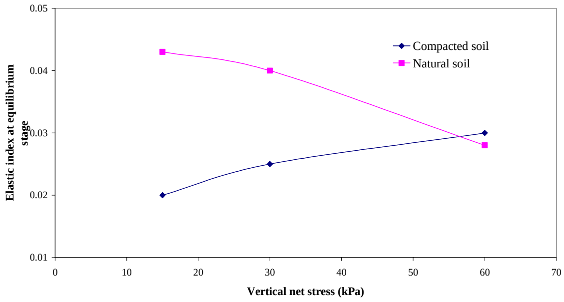


Fig. 7 - Variation of elastic index at the equilibrium stage for the compacted and natural samples

The plastic strains can be calculated by the difference between the total strains and the elastic strains for each suction variation between 0 and 8 MPa. The elastic strains are obtained by the elastic index at equilibrium stage presented in Fig. 7 for the different applied stress. The (plastic strain/ elastic strain) ratio on function of the number of cycles are plotted in Fig. 8 for the compacted soil and in Fig. 9 for the natural soil. The positive value of (plastic strain/ elastic strain) ratio presents the shrinkage phase for the compacted soil and the swelling phase for the natural soil. It can be observed for the compacted soil that the equilibrium state is already reached under vertical stress of 15 and 30 kPa after three wetting and drying cycles and only one additional suction cycle may be sufficient at 60 kPa to possess this elastic behaviour. These results also show that the reversible state is not obtained for all the natural samples while it may be reached sooner for the sample at vertical stress of 60 kPa.

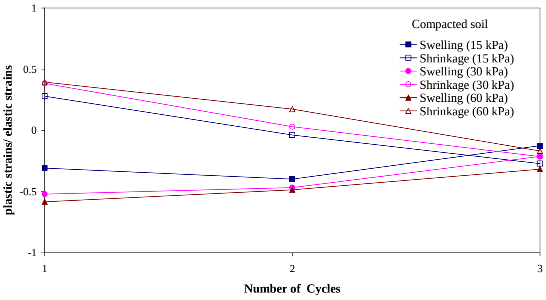


Fig. 8 - Plastic stains evolution during the suction cycles on the compacted material (C1, C2 and C3 tests)

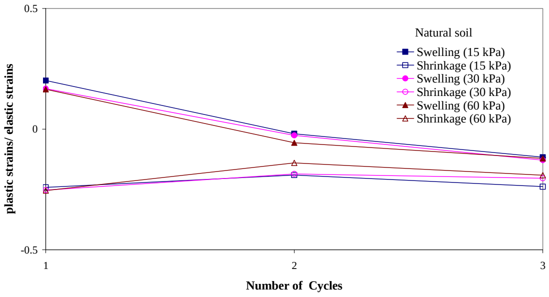


Fig. 9 - Plastic stains evolution during the suction cycles on the natural material (N1, N2 and N3 tests)

CONCLUSION

The influence of the suction cycles on the behaviour of two swelling soils: compacted bentonite/silt mixture and natural soil was studied. The suction cycles were imposed by the osmotic method ranging between 0 and 8 MPa at the constant mechanical loadings (15, 30 and 60 kPa). We can state that the soil fabric has a significant influence on the swelling or shrinkage accumulation during the suction cycles: the shrinkage accumulation is highly significant for the compacted macrostructural soil and the natural microstructural samples show the swelling accumulation during the wetting and drying cycles. The volumetric strains converge towards an equilibrium elastic stage at the end of the shrinkage and swelling cycles. The convergence to this elastic state is much more rapidly obtained for the lower applied stresses on the compacted soil and for the higher stresses on the natural soil.

ACKNOWLEDGEMENT

One part of this work on the natural soil was carried out within the framework of the national research project: Analysis of Shrinkage-Swelling Phenomenon Influence on the Structures (ARGIC) financed by the French National Agency of Research (ANR).

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