Suction variations and soil fabric of swelling compacted soils

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Abstract: This study addresses firstly the soil fabric variations of loose and dense compacted soil samples during a single wetting/drying cycle at suctions between 0 and 287.9 MPa using mainly the mercury intrusion porosimetry (MIP) tests. Two suction techniques were employed to apply this wide suction range: the osmotic technique for suctions less than 8.5 MPa, and the vapor equilibrium or salt solution technique for suctions higher than 8.5 MPa. Secondly, the soil water retention curves (SWRCs) were predicted by the MIP test results for both loose and dense soil samples. A reasonable correspondence between MIP results and SWRCs was found on the wetting path at lower suctions close to saturation and on drying path at higher suctions.

Key words: expansive soil; experimentation; modelling; drying/wetting cycle

1 Introduction

The clayey materials are likely to be subjected to complex suction/stress paths, causing many disorders in structures built on their surfaces (shallow foundations, retaining structures, landfill liner systems, earth dam cores, etc.) and also buried structures (tunnels, drains, deep foundations, etc.). In this context, it is important to study the hydro-mechanical behaviours of these materials to better control their use.

The complex hydro-mechanical behaviours of expansive materials are basically connected to their fabrics [1–3], which become the main subject of the additional studies on the micro- and macro-structure [4–11].

The determination of soil water retention curve (SWRC) is time-consuming and work-intensive. Therefore, important efforts have been undertaken to develop models describing the relationship between water potential and soil water content or degree of saturation from soil properties routinely measured in laboratory. Granulometric composition and soil particle density were initially used. Recently, several authors have connected mercury intrusion porosimetry (MIP) results to soil hydraulic properties, especially the SWRC in which soil structure parameters such as pore size distribution (PSD) were used in the models [12–17]. Further investigations are also needed to complete these experimental results.

In this context, this study addresses the following main issues:

(1) First, the influence of initial compaction pressure on the fabric of a bentonite/silt mixture was presented mainly using the MIP technique.

(2) Second, the void ratio as well as the soil fabric variations of loose and dense soil samples were studied during a single wetting/drying cycle at suctions between 0 and 287.9 MPa. Two suction techniques were employed to apply this wide suction range: the osmotic technique for suctions less than 8.5 MPa, and the vapor equilibrium or salt solution technique for suctions higher than 8.5 MPa.

(3) Third, the SWRCs of these clayey soils were inferred from the MIP test results.

2 Experimental techniques

MIP tests were used to study the soil fabric evolution of the studied soils at different imposed
suction levels. In the porosimeter, the mercury pressure was increased continuously from 0.007 to 410 MPa (intruding apparent pore diameters from 0.004 to 300 µm). MIP tests required dehydrated samples to be measured less than 3 000 mm³ (limited by the sample holder and the cell stem volume). From each sample, MIP specimens were carefully trimmed into cubes firstly, subsequently freeze-dried to remove the pore water, and finally MIP specimens were kept in a desiccator until testing.

The necessary assumption is made that larger pores can be intruded from the outside without mercury penetrating through smaller pores. However, it is possible that large pores in the interior of the specimen, because of the bottle neck effect, are not intruded until high pressures are reached and their volumes are necessarily interpreted as belonging to much finer pores. Therefore, in this paper we prefer to use the term “pore access diameter” rather than “pore diameter”.

Freeze-drying was selected for our MIP study as an alternative to oven-drying to prevent the effects of shrinkage in the process of drying. Soil pieces were quickly frozen with liquid nitrogen (temperature of −196 °C) and then placed in a freeze-drier for at least 72 h for the sublimation of water before the MIP tests.

Experimental investigation into the behaviours of swelling soil is a difficult task because its hydraulic conductivity is low and its suction can fluctuate between 0 and several hundreds of megapasal. Since there is no unique technique to cover this range of suction, at least two suction control techniques are required.

The first is the osmotic method. The principle of this method is to put a soil sample and a macromolecular solution of polyethylene glycol (PEG) into contact with a semi-permeable membrane between them [18]. Higher concentrations of the solution result in higher imposed suctions [19–22]. The molecular weight of PEG chosen for these tests was 6 000 Da (1 Da = 1.660 5×10⁻²⁴ g), which made it possible to impose a maximum suction of 8.5 MPa.

For higher suctions, the only available method is the vapor equilibrium technique. This method consists of inserting a sample into a container, which includes different salt solutions. The soil sample absorbs or desorbs water until the potential equilibrium is reached. The imposition of a given relative humidity (RH) to a soil sample allows its suction to be controlled considering Kelvin’s equation. This method, however, is influenced by a certain number of parameters such as the type of solution, the pressure and the temperature. In order to limit the influence of the temperature, salt which is less sensitive to temperature was selected [23]. They made it possible to impose suctions between 8.5 and 287.9 MPa.

### 3 Studied materials

This study was conducted on a mixture of 40% silt and 60% 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% calcium montmorillonite. The main geotechnical properties of the mixture are the liquid limit of 87%, the plasticity index of 22% and the specific gravity (G) of 2.67. The size of the particles used to prepare the samples is less than 400 µm (obtained by sieving). The initial dry densities of the compacted soil are about 1.27 and 1.55 Mg/m³, respectively, under two vertical pressures of 1 000 and 3 000 kPa with an initial water content of 15%. The initial height of the samples is (10 ± 0.5) mm and their diameter is 70 mm. The total suction measured by the filter paper technique [24] is about 20 MPa for both soils. The measurement of the swelling potential and the swelling pressure was carried out using the free swelling method [25]. The sample with an initial dry density of 1.55 Mg/m³ presents higher swelling potentials, 25% against 17%, as well as higher swelling pressures, 850 against 170 kPa.

The PSD of both compacted materials was evaluated by the MIP tests. Figure 1 presents the variation of incremental mercury intrusion volume versus pore

![Fig.1 Results of MIP test on dense and loose bentonite/silt mixtures.](image-url)
access diameter. This distribution shows two distinct structural levels, which is one of the fundamental characteristics of the clayey soils: micro- and macro-structure [26, 27]. The dominant diameter of about 7.5 µm corresponds to the macropore of both compacted soils while their micro-structure presents its peak value at 0.011 µm.

It can be stated that the mechanical loading influences only the macro-structure without affecting the micro-structure [8, 28]. There is a transitory pore-size range between micro- and macro-structure, which is not affected by the magnitude of the compaction pressure. This limit range can be considered between 0.04 and 0.15 µm for the loose sample and accordingly, between 0.04 and 1.50 µm for the dense soil. In this stage, we take the maximum possible value of 0.15 µm for the loose sample and 1.50 µm for the dense soil sample as the pore size limits between micro- and macro-structure. The increase in this pore size of the dense samples seems to be reasonable as the macropore was completely eliminated for the higher compaction pressures. According to the Jurin-Laplace law:

$$ s = \frac{2\sigma \cos \theta}{r} \quad (1) $$

where $\sigma$ is the interfacial tension, which is 0.073 N/m for water; $\theta$ is the contact angle (°), which is 0° for water; $r$ is the pore radius (µm); and $s$ is the suction (MPa), the limit of which between micro- and macro-structure can be considered as 2 MPa for the loose sample and 0.20 MPa for the dense sample, neglecting the adsorption phenomenon.

A pore diameter close to 0.004 µm can be taken as the pore size limit between micro- and nano-structure since the PSD is unknown within this range. According to the following experimental results, the suction limit between the micro- and the nano-structure ($s_{nm}$) can be estimated as about 30 MPa, corresponding to a pore size of about 0.008 µm.

4 Soil fabric and suction cycle

The variation of void ratio versus the suction in $e$-lg$s$ plane is presented in Fig.2 for the compacted loose and dense mixtures obtained using two suction imposition techniques: osmotic and salt solution techniques for both samples. Points $A$ and $A'$ present the initial state of the loose and dense samples, respectively, corresponding to the initial suction of 20 MPa and the initial water content of 15%. The initial diameter and height of the samples are 35 and 10 mm, respectively. Thereafter, a wide range of suctions between 0 and 287.9 MPa was applied to the samples with the initial suction of 20 MPa, producing a wetting path for the suctions between 0 and 20 MPa and a drying path for the suctions between 20 and 287.9 MPa. All the saturated samples were finally dried back to a maximum suction of 287.9 MPa.

The following comments can be made based on the obtained results (Fig.2):

(1) In $e$-lg$s$ plane, a “shrinkage limit” suction ($s_{SL}$) can be estimated at about 30 MPa for both samples, and the curves in Fig.2 present a slight slope variation for the suctions higher than 30 MPa. This shrinkage limit suction is not influenced by the wetting/drying cycle.

(2) Another slope variation can be observed on the wetting/drying paths at suctions between 0 and 20 MPa. As the limits of those suctions are modified during the wetting and drying paths, we use the term ($s_{wM}$)sw for the wetting path (swelling) and ($s_{mM}$)sh for the drying path (shrinkage). The suction ($s_{wM}$)sw is about 0.2 MPa for the dense sample and 2 MPa for the loose sample corresponding to the defined suction limit between micro- and macro-structure, ($s_{mM}$)sw, by MIP tests. Both samples present the same suction limit value ($s_{mM}$)sh of 0.3 MPa during the drying path.

(3) At the end of a single wetting/drying cycle at suctions between 0 and 20 MPa, the loose samples presented a shrinkage accumulation while the dense soil produced a swelling accumulation.

According to the experimental results, the shrinkage limit suction ($s_{SL}$) of 30 MPa may correspond to the
suction limit between the micro- and the nano-structure \((s_{nM})\) related to a pore size of 0.008 \(\mu\)m, but it should be mentioned that the capillarity phenomenon is not the only dominant mechanism within this pore size range. Generally, the shrinkage or swelling accumulation of samples can be related to values of \((s_{nM})_w\) and \((s_{nM})_d\): the initial value \((s_{nM})_w\) is higher/lower than the initial value \((s_{nM})_d\) for the loose/dense samples. Both loose and dense samples showed the same slope for the suctions controlled by macro-structure during the wetting/drying cycle. However, the equivalent micro-structural slope during the wetting/drying cycle seems to be influenced by the soil initial state. The dense samples presented a smaller micro-structural slope.

For the loose samples, the incremental mercury intrusion volume versus the pore diameter in saturated state is compared with the soil initial state at a suction of 20 MPa in Fig.3. The saturation modifies the diameter limit between micro- and macro-structure to 1 \(\mu\)m corresponding to a suction limit value \((s_{nM})_w\) of 0.3 MPa. As well, the macro-structure is highly increased in the saturated phase. We believe that the dense samples have the same soil fabric with a macro-structural quantity less significant but the same pore size limit between micro- and macro-structure of 1 \(\mu\)m at the end of wetting path as obtained in Fig.2.

As the soil behaviours become completely elastic after several wetting/drying cycles [3], we believe that the \((s_{nM})_w\) and \((s_{nM})_d\) become completely the same at this equilibrium stage. This point will be the main subject of our future investigations.

Fig.3 Influence of saturation on soil fabric of a loose bentonite/silt mixture.

5 Soil fabric and SWRC

Figure 4 shows the main wetting and drying paths for the studied soils in the saturation-suction plane where the hysteresis phenomenon is less significant for dense samples. Additionally, the MIP results can be used to determine saturation-suction relationships (Fig.4). It was supposed that the mercury intrusion procedure can become assimilated to a desorption path of the SWRC in the matric suction range between 0.01 and 80 MPa by applying increasing external air pressure to an initially saturated sample to gradually dry soil. Thus, mercury injection with a contact angle \((\theta_M)\) of 140° and interfacial tension \((\sigma_{Hg})\) of 0.484 N/m is equivalent to the ejection of water from the pores with a contact angle \((\theta_w)\) of zero for the same pore diameter, leading to the following relation between the suction \((s)\) and the intrusion pressure \((p)\):

\[
s = u_s - u_w = \frac{\sigma \cos \theta_w}{\sigma_{Hg} \cos \theta_M} p = 0.196 p \tag{2}
\]

The degree of saturation of the pores is not filled by mercury, \(S_s = 1 - S_{sw}\), where \(S_{sw}\) is the degree of saturation of the voids filled by mercury, \(S_{sw} = n / n_0\), where \(n\) is the porosity of the pores filled by mercury, and \(n_0\) is the total porosity. However, this last relation does not consider the adsorbed water on the mineral surfaces and the residual water corresponding to the porosity is not filled by mercury. The residual
degree of saturation \( (S_{\text{res}}) \) is obtained at a total suction of 80 MPa related to the maximum intrusion pressure of 450 MPa. This was taken as about 30% for both compacted samples. To take into account this residual degree of saturation, Romero et al. [13] also proposed

\[
S_s = 1 - S_{\text{res}} + \frac{S_{\text{res}}}{S_{\text{sat}}} S_{\text{sw}}
\]

where \( S_{\text{sat}} \) is equal to 100% in the saturated state.

The MIP test results remain much closer to the wetting path at suctions between 0 and 80 MPa for both soils. For the higher suctions, it presents a good correspondence to the drying path since the hysteresis phenomenon is negligible within this suction range.

The results for a compacted clay [12] also underestimated the measured water content based on the MIP data when analyzing a suction range greater than 0.01 MPa. Similarly, comparison of predictions of the water retention curve with measurements on Boom clay [13] showed that the MIP predictions underestimated water content at suctions greater than 0.04 MPa. The differences between MIP estimation and SWRC results [15–17] could arise due to different sample sizes used for the MIP tests and the water retention curve determination. It may be also related to the water and dissolved salts produced on clay fabric compared to a less active mercury intrusion [13].

6 Conclusions

This study addresses firstly the soil fabric variations of compacted samples during a single wetting/drying cycle at suctions between 0 and 287.9 MPa mainly using the MIP tests. Two suction techniques were employed to apply this wide suction range: the osmotic technique for suctions less than 8.5 MPa, and the vapor equilibrium or salt solution technique for suctions higher than 8.5 MPa. Generally, the shrinkage or swelling accumulation of samples can be related to values of \( (S_{\text{sw}})_{\text{sw}} \) and \( (S_{\text{sw}})_{\text{sh}} \): the initial \( (S_{\text{sw}})_{\text{sw}} \) value is higher/lower than the initial value \( (S_{\text{sw}})_{\text{sh}} \) for the loose/dense samples. We believe that after several wetting/drying cycles, the values of \( (S_{\text{sw}})_{\text{sw}} \) and \( (S_{\text{sw}})_{\text{sh}} \) become completely the same.

Secondly, the SWRCs were predicted by the MIP test results. A reasonable correspondence between MIP results and SWRC was found on the wetting path for lower suctions close to saturation and on drying path for higher suctions.

References


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