Effect of stress on water retention of needlepunched geosynthetic clay liners

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EFFECT OF STRESS ON WATER RETENTION OF NEEDLEPUNCHED GEOSYNTHETIC CLAY LINERS

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ABSTRACT

Geosynthetic clay liners (GCLs) are placed at the bottom of waste disposal facilities where they hydrate from the subsoil and eventually from a hydraulic head on geomembranes (GMs) defects. Predicting hydration behavior of GCLs requires knowledge of the water-retention properties of the GCL along wetting paths. Given that GCLs could be subjected to different ranges of vertical stresses that are induced by the weight of the supported waste, the confining stress could affect water-retention properties of GCLs and should be investigated. To do so, a laboratory methodology to establish the water-retention curves (WRCs) of needlepunched GCLs under stress was undertaken. Various constant vertical stresses corresponding to different weights of the supported waste were applied to GCL specimens placed in controlled-suction oedometers. Suction values were selected so as to mimic a wetting path from the initial dry state to zero suction. Suction was controlled by using controlled suction techniques with controlled humidity imposed by a saturated saline solutions and using the osmotic technique with polyethylene glycol (PEG) solutions. Measurements were undertaken on oedometer systems as to apply confining stresses and have been complemented by standard saturated oedometer swelling tests. The data obtained confirm that increasing the stress on to the GCL results in less, albeit faster, water uptake, which could emphasize on recommendations about rapidly covering GCLs after they are placed at the bottom of a waste disposal facilities. Finally, the potential validity of the state-surface concept, which was developed in unsaturated soil mechanics, is discussed using van Guenuchten's and Fredlund and Xing's equations for water retention curves.

Keywords: geosynthetics, geosynthetic clay liner, unsaturated conditions, water retention curve, suction, confining stress.

1. INTRODUCTION

Geosynthetic clay liners (GCLs) are composite materials used in geotechnical and geoenvironmental engineering applications. Specifically, they serve as barrier systems in landfill liners, tailing ponds or dams (Bouazza, 2002). GCLs have gained worldwide acceptance because once they are hydrated and confined, they represent excellent hydraulic barriers. GCLs consist of a layer of bentonite inserted between two geotextiles linked together by various means (stitching, needle punching, heat bonding, wrapping, etc.). The suction of the bentonite contained in GCLs can be as high as 1000 MPa (Beddoe et al., 2010).

When installed in composite liners, GCLs hydrate under a compressive stress corresponding to the overburden load. After that, the GCL hydrates typically from both the liquid flux through defects in the geomembrane (GM) and the transfer of vapour and liquid water from the underlying soil through the GCL (Azad et al., 2011; Beddoe et al., 2010). Assuming a typical depth of waste deposits of between 20 and 30 m and adopting a density of 800 to 1000 kg/m^3 for the waste, vertical stresses applied to GCLs at the bottom of deposits may reach 300 kPa.

The capability of a GCL to serve as a barrier to fluids (either liquid or gas) is intimately linked to the uptake of moisture by the bentonite. However, there is no guarantee that the GCL will reach full hydration before leakage begins through a defective geomembrane. Accurately predicting the hydraulic behavior of composite liners requires knowledge of both the water retention curve (WRC) of the GCL and its volumetric changes during hydration. Many experimental studies have investigated the water-retention properties of GCLs (Daniel et al., 1993; Barroso et al., 2006b; Southen and Rowe, 2007; Abuel Naga and Bouazza., 2010; Beddoe et al., 2010; Beddoe et al., 2011; Hanson et al., 2013; see Table 1). In addition, to quantifying the transient hydration of GCLs under experimental unsaturated conditions, Siemens et al. (2011, 2013) have done numerical simulations on the transient hydration of GCLs. They assessed the impact of two confining stresses (10, 100 kPa) on the rate of hydration and the moisture equilibrium content of GCLs.

Most investigations into water retention in the wetting path (Daniel et al., 1993; Barroso et al., 2006; Beddoe et al., 2010; 2011; Hanson et al., 2013) have been done without considering the confining stress effect which affects the water-retention properties of the GCL (as observed in other bentonite-based materials). For example, in radioactive waste management, Yahia-Aissa et al. (2001) demonstrated that volume constraint of compacted bentonite leads to significantly less water retention at saturation. This effect was later confirmed by Lloret et al. (2003) and Villar et al. (2003), who used the same approach. Southen and Rowe (2007) investigated the effect on water-retention in GCLs of different confining stresses (3 and 100 kPa) applied along a drying path. The effect of confining stress applied along a wetting path was investigated by Abuel-Naga and Bouazza (2010) (with a single stress of 50 kPa) and by Beddoe et al. (2011) (with a small stress of 2 kPa). Siemens et al. (2013) numerically studied the effect of confining stresses of 2 kPa and 100 kPa on water retention in GCLs.

These studies did not investigate water retention along a wetting path for the larger range of confining stresses that corresponds to deeper waste deposits (for example in the case when a hydraulic head exist on the GM overlying the GCL is presenting holes).

To better understand the hydromechanical response of GCLs, this paper presents the results of an experimental program designed to investigate the effect of confining stress applied along the wetting path of the WRC of GCLs. The WRC was determined based controlled suction techniques adapted to oedometer equipment with saturated saline solutions and osmotic technique with polyethylene glycol (PEG) solutions. Measurements were complemented by standard saturated oedometer swelling tests to obtain water retention properties at zero suction. In the following, WRCs at the wetting path, their experimental determination, and their relevance with respect to GCL issues are first briefly introduced. Second, the suction-control methods that were applied to the GCL are described. Finally, the results obtained are presented and compared with published data. Two well-known WRC equations (van Guenuchten's and Fredlund and Xing's) are fit to the data obtained and an explanation of the effect of stress is proposed.

2. WATER-RETENTION CURVES

2.1.Water-retention along wetting path in geosynthetic clay liners

GCLs have a composite structure consisting of geotextiles and bentonite. When the GCL is under unsaturated conditions, Abuel Naga and Bouazza (2010) modeled the structure of a GCL as a double-porosity material with two distinct air-entry values and two residual water contents corresponding to that of the geotextile and that of the bentonite. Based on the fact that GCLs present composite structures, along the wetting path, the GCL's bentonite will swell and could squeeze out to occupy some of the pore space of the geotextile component with the confining stress .

In this context, it is important to find a suitable methodology for investigating the water retention of GCLs along the wetting path over the entire relevant suction range by examining the effects of confining stress on GCL water retention.

2.2.Techniques to determine water-retention curve of geosynthetic clay liner

Some methods recently adopted to determine the WRCs of GCLs have been described by Abuel Naga and Bouazza (2010), Beddoe et al. (2010), and Zornberg et al. (2010). Based on Figure 1, it is recommended to combine at least two different techniques to cover the entire suction range of GCLs. As seen in Table 1, methods used to determine the WRC of GCLs include (i) vapour equilibrium (Daniel et al. 1993) and (ii) axis-translation techniques based on plates or membrane extractors (Southen and Rowe, 2004; 2007; Hanson et al., 2013). (iii) thermocouple psychrometer (Daniel et al., 1993; Abuel-Naga and Bouazza, 2010), (iv) the filter-paper technique (Barroso et al., 2006b; Hanson et al., 2013), (v) high-capacity tensiometers (Beddoe et al., 2010 ; 2011), and (vi) capacitive relative-humidity sensors (Abuel Naga and Bouazza, 2010 ; Beddoe et al., 2010 ; 2011 ; Hanson et al., 2013).

Some methods have shown their limitations for use with GCLs. For example, sensors such as thermocouple psychrometers are irrelevant at low suction (<1 MPa), particularly because of their significant temperature sensitivity (Daniel et al., 1993; Abuel Naga and Bouazza, 2010), and fungi that develop on filter paper could affect the results of the filter-paper technique if test protocol is not followed (Barroso et al., 2006b).

This study used to present an original methodology for establishing water retention curve of GCLs under wetting path and confining stress that takes into account the composite structure of GCLs.

3. MATERIALS AND METHODS

3.1.Geosynthetic clay liner properties and preperation

A needle-punched GCL containing granular sodium bentonite was used. The cover geotextile was woven and the carrier geotextile was needle punched. The mass per unit area M_b of bentonite was 5.80 kg/m^2. The average thickness of the GCL was 7 mm. The basic features of the measurements done to determine the WRCs of the GCL are summarized in Table 2. The GCL sample was cut into 7-cm-diameter specimens by using a cookie cutter and then inserted in the oedometer in which suction-control methods were applied under various stresses. These methods are presented in Sections 3.2.1 and 3.2.2.

To obtain results that are independent of the GCL bulk void ratio, specimens were selected to ensure a relatively uniform mass per unit area M_b of bentonite. The selection has been made by cutting 20 GCL specimens then chooses the closest values of mass of GCLs.

3.2. Techniques to establish the water retention curve of geosynthetic clay liner

Three methods were used to determine water retention curve of geosynthetic clay liner. Two method were used to control the suction using saturated saline solutions (controlling the total suction), and the osmotic technique (controlling the matric suction). These two techniques were adapted to oedometer cells where GCL specimens were confined. It is not necessary to adjust total suction values for the matric suction controlled by the osmotic oedometers because it was deemed irrelevant for the range of total suctions measured for GCLs (Beddoe et al. 2011).This approach allowed (i) the application of a controlled vertical stress; and (ii) the coverage of the wide range of suction required to establish the WRC of the GCL along the wetting path starting from the natural water content. An additional standard saturated oedometric measurement was also done to obtain data at zero suction.

3.3. Method used to control geosynthetic clay liners' suction

3.3.1. Control of relative humidity of vapour by oversaturated salt solution (SS measurements)

This technique consists of controlling the total suction by controlling the relative humidity around the specimen in a closed loop in which the vapour generated by oversaturated salt solutions (SS) is circulated. This technique is preferably used with relative humidity less than 97% (suction greater than 4.2 MPa). The suction applied depends on the nature of the salt used, on temperature, and on air pressure. In this study, the vapour-equilibrium technique was used to hydrate the GCL starting from its initial situation.

The relative humidity R_{H} is linked to suction ψ through Kelvin's law:

$$\psi = u_{\mathrm{a}} - u_{\mathrm{w}} = -\frac{RT}{Mg}\ln\left(R_{\mathrm{H}}\right), \tag{1}$$

Where ψ is the suction (MPa), u_{a} is the air-pore pressure (MPa), u_{w} is the water-pore pressure (MPa), R is the universal gas constant (R = 8.314 J·Mol^{-1}·K^{-1}), T is the temperature in kelvins, M is molecular weight of water (18×10^{-3} kg/mol), and g is the acceleration due to gravity (m/s^2).

In this study, two different salts were used: potassium sulfate (K_2SO_4) and potassium nitrate (KNO_3). Their chemical properties at 20 °C are presented in Table 4. The suction applied is 4.2 MPa for K_2SO_4 and 8.5 MPa for KNO_3.

3.3.2. **Control of matric suction using osmotic technique**

The osmotic technique (Delage and Cui 2008) is based on controlling the matric suction by using a polyethylene glycol (PEG) solution at various concentrations. The concentrations are determined by a calibration curve initially proposed by Williams and Shaykewich (1969). The osmotic method makes it possible to control suction from 0 to 10 MPa (Delage et al. 1998). The most common PEGs used in geotechnical measurements have a molecular weight of 6000 or 20000 Da (1 Da = 1.66^{-24} g) (Delage and Cui, 2008). The calibration curve used to link the controlled suction ψ to the PEG solution concentration c was initially obtained by Williams and Shaykewich (1969). It can be expressed as (Delage et al. 1998)

$$\psi = 11c^2 \tag{2}$$

The suction ψ is in MPa and c is expressed in g PEG/ g water.

This equation indicates that the greater the solution concentration, the greater the imposed suction. Semi permeable membranes are defined by their molecular weight cutoff (MWCO). A membrane with a MWCO of 14 000 kg/mol has to be used with a PEG solution of 20 000 Da (Delage et al., 2008).

The main advantage of this technique compared with using oversaturated saline solutions is that PEG solutions at controlled concentrations provide control of suction when the suction is small. To ensure stable PEG concentration, a large bottle of PEG (1000 cm^3) was used, as indicated in Figure 2 (b). The suctions applied by using the PEG solutions cross out to 0.1, 0.5, 1, and 2.8 MPa. These values were obtained by using solutions of PEG (20 000 Da) with concentrations of 0.09, 0.21, 0.30, and 0.50 g PEG/g of water, respectively. Tests were also performed by using pure water, which resulted in zero applied suction.

3.4.Specimen installation and measurements

Saturated salt solution techniques and the osmotic technique were adapted to control GCLs' suction into oedometers cells. A series of four GCL specimens of comparable mass (Table 3) were carefully placed into the oedometer cells, with special care taken not to lose bentonite grains from the edge of the specimens. To speed up the vapour circulation process in the case of saturated salt solution technique, that can take several weeks for high-density plastic clays, vapour transfer through the specimen or along the boundaries of the specimen can be forced by a venting circuit driven by an air pump (Yahia-Aissa, 1999; Blatz and Graham 2000). As seen in Figure 2 (a), the closed-loop venting circuit consists of the following elements connected in series: a porous stone at the base of the oedometer, a pneumatic pump, and a bottle containing the oversaturated saline solution in a temperature-controlled bath.

In the case of osmotic technique method, the oedometric equipment (Figure 2 b) was used according to Kassif and Ben Shalom (1971)'s set up and modified later by Delage et al. (1992).

The PEG solutions were circulated over a closet circuit using a peristaltic pump which insures the water transfer between the membrane and the GCL specimen.

The initial suction of GCLs was evaluated by measurements done on two comparable GCL specimens by using a WP4 dew-point tensiometer (Decagon) that provided suction values of 135 MPa at water contents of 9.63%, respectively. Each of the four specimens was then submitted to one of the four confining stresses: 10, 50, 100 and 200 kPa. These stresses were applied prior to decreasing the suction along the wetting path from an initial suction of 135 MPa. The vapour circulation using salt solutions and liquid circulation using PEG solution started when there was no change noticed on the GCL thickness. Two sets of four specimens were used for both the oversaturated saline solution (four stresses were applied under imposed suctions of 4.2 and 8.5 MPa) and the PEG solution (four stresses were applied under imposed suctions of 0.1, 0.5, 1, and 2.8 MPa). The room temperature was maintained at 21 ± 0.5 °C. The height of the specimen was monitored by a displacement gauge. Equilibrium was evaluated when swell measurements reached 90% of the maximum swell (equilibrium criteria for hydration provided by NF P84-705 as follows :

$$\Delta h = \Delta h_{90} \frac{t}{t_{90} + t} \tag{3}$$

Δh_{90} corresponding to the maximum swelling at 90% of maximum swelling and t_{90} time corresponding to 90 % of maximum swelling). We could thus determine time reaching equilibrium by estimating the maximum swelling and establishing a criteria of equilibrium which is reaching 90% maximum.

- Height measurements was always undertaken on the center of the specimen thanks to a plate as for conventional oedometer,

Gravimetric water contents were determined at the end of each measurement (French standard NF P 94-050).

4. RESULTS AND DISCUSSION

The GCL specimens were measured using both the SS and PEG procedures. Some standard saturated oedometer measurements (OETs) were also conducted. The measurement program is summarized in Table 3 and used suction between 0 and 8.5 MPa. For each measurement a dry specimen was loaded into the oedometer and subjected to the desired stress prior to imposing a suction less than the initial suction (135 MPa). The specimens were under constant vertical stress during the measurements.

4.1.Effect of confining stress on water-retention curve

Figure 3 shows the suction as a function of gravimetric water content obtained with the SS, PEG, and OET methods together with the point corresponding to the natural water content with an initial suction of 135 MPa. The four points plotted for each applied suction (either by SS or PEG) corresponds to the four different vertical loads applied. As is typically found, the smaller the suction controlled, the higher the water content measured under the different confining stresses between 10 and 200 kPa.

These results show that the influence of the applied stress is almost negligible for suctions greater than 2.8 MPa. In this range of applied suction, the water content is comparable for the four applied vertical loads. These results are consistent with those of Abuel Naga and Bouazza (2010), who highlighted the insignificant effect of a 50 kPa confining stress on the water retention of GCLs at suctions greater than 10 MPa, where swelling and water uptake were less than at smaller suctions. This is the reason why only three normal stresses (<10 kPa, 100 kPa, and 200 kPa) were applied to specimens for suctions greater than 2.8 MPa.

At suctions less than 2.8 MPa, the effect of the confining stress on the GCL water content is clearly apparent. At a given suction, more water is retained for a smaller confining stress. Maximum water content occurs at zero stress (represented here in the semi-log graph of Fig. 4 at 0.1 kPa) with values ranging from 85% (less than 200 kPa confining stress) to 160% (less than 10 kPa confining stress).

Figure 4 shows the change of the thickness of the oedometer specimens that occurred during the measurements described in Figure 3. Figure 4 shows the change of the thickness volume of the oedometer specimen as a function of time obtained under the four applied vertical stresses (10, 50, 100, and 200 kPa) at controlled suction of 8.5, 4.2, 2.8, 1, 0.5, 0.1, and 0 MPa, respectively.

The initial response is a rapid compression observed when applying the load, which is typical of unsaturated soils and corresponds to the rapid expulsion of air. All initial settlements should be comparable. However, this is actually not the case because the initial mass differs between the five different GCL specimens, as seen in Figure 5 and Table 3. Figure 5 shows that a dispersion of about ±0.5 in void ratio occurs for all stresses, a range comparable to that obtained from the data of Beddoe et al. (2011) at a stress of 2 kPa. The data of Abuel Naga and Bouazza (2010) also concur with this observation. Figure provides some information on the compression properties of the dry GCL.

After the initial rapid settlement (which not exceed 2 hours), the GCL is subjected to controlled suction from the saturated saline solution for the greater suctions or from the controlled-concentration PEG solutions for lower suctions down to zero).

The increase of the settlement registered either when the suction decrease could be related to some collapse mechanism. This latter represents an additional settlement of GCLs specimens' occurring after the stabilization of the compression resulting from the application of the confining stress. As have been explained by Tadepalli and Fredlund (1991), collapse mechanism occurs with soils typically presenting an open type of structure with many void spaces, which give rise to a metastable structure. It could be believed in this case that the application of the confining stress and the decrease of the suction by controlled suction techniques could lead to structural arrangement of grains bentonite's particules into GCLs specimens. Collapse mechanism could be observed for example for 200 kPa of applied confining stress. So Figure 4 shows that the change in GCL volume depends strongly on the confining stress the applied suction, and the grain size distribution of the bentonite as part of the GCL.

Under the highest suction of 8.5 MPa and after the initial compression process, the GCL and the GCL volume does not significantly change, which shows that the decrease in suction from the initial value of 135 MPa down to 8.5 MPa does not significantly affect the overall volume in spite of some water being absorbed by the specimen. This means that hydration occurs within the bentonite grains with little volume change of the grains themselves.

Volume changes induced by suction decrease under constant stress and are more apparent under suctions less than 1 MPa (Figure 6). As could be seen in Figure 6, change in thickness is very close for each confining stresses for suction higher than 1 MPa.

Under this suction, the changes in volume are typical of unsaturated swelling soils. Specifically, the results show:

- (i) no swelling at the largest stress (200 kPa), which corresponds to the collapse mechanism,
- (ii) no significant swelling at 100 kPa stress,
- (iii) swelling at the two smaller stresses (10 and 50 kPa).

Under the suction of 0.5 MPa, the final settlement under a 200 kPa compressive stress is −2 mm (comparable to that at a suction of 1 MPa), whereas some settlement due to suction increase is observed for a compressive stress of 100 kPa. As expected, the swelling observed for smaller stresses (10 and 50 kPa) is greater under a suction of 0.5 MPa compared with that obtained previously under a larger suction of 1 MPa.

Greater swelling is observed when the specimen is under 0.1 MPa suction. Settlement still occurs under 100 and 200 kPa of compressive stress (the constant value observed at stresses below 100 kPa is due to a technical problem related to a blocked oedometer piston). For compressive stresses less than 200 kPa, the settlement changes less (<2 mm) than at 0.5 MPa of suction and 200 kPa of compressive stress.

Finally, for the GCL specimen under zero suction (obtained by circulating pure water in the osmotic oedometer), the results agree well with previous measurements: no swelling occurs under a compressive stress of 200 kPa, whereas all other GCL specimens swell when subjected to lower stresses (100, 50, and 10 kPa).

The decrease in porosity and change in the pore structure of the bentonite layer under greater compressive stress is expected to result in a reduction of the GCL's saturated conductivity. To investigate this aspect, constant-head saturated permeability measurements were done on GCL specimens provided from the same GCL sample in an oedopermeameter (230 mm in diameter and 9 mm in height) under a 10 cm hydraulic head, using the protocol of the French standard NF P84-705. Once the specimens were saturated, the constant flow rate traversing the specimens was measured, providing the saturated hydraulic conductivity via Darcy's law. The results show that the hydraulic conductivity of a saturated GCL decreased by 59% from 3.10×10^{-11} to 1.85×10^{-11} m/s when the confining stress was increased from 10 to 200 kPa.

4.2. Comparison with published data

Figure 7 shows the gravimetric water content as a function of suction under 10 kPa compressive stress obtained in the present study. These data are compared with similar data obtained under free-swell conditions in other studies of GCLs (Barroso et al., 2006b; Daniel et al., 1993; Hanson et al., 2013) and in studies of compacted bentonites for research into radioactive-waste disposal (Yahia-Aissa et al., 2001; Villar and Lloret, 2004; Delage et al., 2006). Note that, due to compaction, bentonite used for radioactive-waste disposal is significantly denser than the granular bentonite contained in GCLs. The suction applied to the compacted bentonite is therefore generally higher.

The data shown in Figure 7 indicate a relatively good agreement between the results obtained in the present study with GCLs and published results from studies of either GCLs or compacted bentonites. The only exception is for FoCa7 clay (Yahia-Aissa et al., 2001), but the difference here is attributed to the material not being a pure smectite and having a significant calcium content. This agreement confirms that WRCs are independent of the as received density of bentonites, which is attributed to water adsorption occurring within the bentonite grains. This means that water absorption is mainly governed by local water-clay physicochemical interactions within the bentonite grains.

Figure 8 compares the data of this work with published WRCs determined from GCLs under confining stress (Abuel Naga and Bouazza, 2010; Beddoe et al., 2011). Not surprisingly, WRCs obtained from GCLs under confining stress agree better with our results, illustrating clearly the significant influence of confining stress on the water-retention properties of GCLs. The results of the present study agree reasonably well with the data obtained by Abuel-Naga and Bouazza (2010) from GCLs under 50 kPa of confining stress. The agreement with the data of Beddoe et al. (2011), obtained from a GCL under a small confining stress of 2 kPa, is less satisfactory: they observed higher water content at high suction (above 20 MPa) and lower water content at low suction (below 0.1 MPa). Note that significant differences existed between GCLs 1, 2, 3 and 4 tested by Beddoe et al (2011). In addition, compared with the granular bentonite used in the GCLs for present study, the bentonite powder in the GCLs used by Beddoe et al. (2011) is more strongly confined because of a thermal treatment and the scrim reinforcement, which results in a much more strongly bonded structure compared with the needle-punched structure of the GCL used in this study. These data tend to show an effect of the GCL structure on its water retention behaviour: a stronger structure could lead to a significant decrease in water uptake and reduced swelling of the bentonite.

4.3. Equations for water retention as a function of stress

A quantitative equation for water retention in a GCL under various stresses is derived based on two well-known equations for WRCs: namely, that of van Genuchten (1985) and of Fredlund and Xing (1994). The van Genuchten equations is

$$\theta(\psi,T_0)=\theta_r+\frac{\theta_s-\theta_r}{\left(1+|\alpha\psi|^n\right)^m},\quad \theta_r\le\theta\le\theta_s, \tag{4}$$

where θ is the volumetric water content (m^3/m^3),T0 is the temperature =21 ± 0.5 °C, θ_r is the residual water content (m^3/m^3) at high suction, θ_s is the water content (m^3/m^3) at zero suction, ψ the suction (m), and α (1/m), n, and m are fitting parameters (with $m = 1 - 1/n$).

In clayey soils, θ_r is often assumed to be equal to zero (Babu et al., 2002). In this case, Eq. (4) simplifies to

$$\theta(\psi,T_0)=\theta_s\left(\frac{1}{\left(1+|\alpha\psi|^n\right)}\right)^m. \tag{5}$$

The Fredlund and Xing equation is

$$\theta=\theta_s\left[1-\frac{\ln\left(1+\psi/\psi_r\right)}{\ln\left(1+10^6/\psi_r\right)}\right]\left[\frac{1}{\ln\left[e+\left(\psi/a_f\right)^{n_f}\right]}\right]^{m_f}, \tag{6}$$

where θ is the volumetric water content (m^3/m^3), θ_s is the water content (m^3/m^3) at zero suction, ψ is the suction (kPa), ψ_r is the residual suction (kPa), and a_f (kPa), n_f, and m_f are fitting parameters.

Given the comparable shapes of the WRCs obtained under the four different stresses (10, 50, 100, 200 kPa), a single set of parameters (excluding θ_s, which depends on the confining stress) was obtained from the van Genuchten and the Fredlund and Xing equations for all four WRCs. For these fits, the WRCs were normalized to their water content at zero suction θ_s. The single set of parameters obtained from both equations is presented in Table 5, together with the values of water content at zero suction θ_s (which remains the only parameter dependent on stress in both equations). The following formulas for θ_s as a function of stress were obtained:

- van Genuchten fit: $\theta_s = 0.9507 e^{-0.003\,\sigma}$ (with R^2 = 0.9665), (7)

- Fredlund and Xing fit: $\theta_s = 0.959 e^{-0.003\,\sigma}$ (with R^2 = 0.9771) (8)

The corresponding fits are shown in Figure 9. Both the van Genuchten and Fredlund and Xing formulas fit reasonably well to the four experimental WRCs, although they slightly underestimate the volumetric water content at the highest stress of 200 kPa.
To account for the dependence on stress of the two WRC equations [Eqs. (5) and (7)] adopted here, two more parameters are necessary. These parameters come from the equations for water content as a function of stress at zero suction θ_s, which are expressed in Eqs. 7 and 8.

The volumetric water content θ as a function of suction ψ and applied stress σ are represented in three-dimensional graphs in Figs. 10(a) and 10(b) for Eqs. (5) and (6), respectively. These representations are comparable to state surfaces that, along a wetting path, govern the changes in volume and degree of saturation of unsaturated soils (Matyas and Radhakrisna 1968).
Each surface plotted in Figure 9 clearly shows the dependence of the volumetric water content on the applied vertical stress as suction decreases. When the vertical stress increases from 0 to 300 kPa, the water content increases from 0.39 to 0.92 at zero suction whereas it increases from 0.09 to 0.28 at a 5 MPa suction. This kind of representation makes it possible to predict the volumetric water content and other state parameters of unsaturated GCLs under specific site conditions.

5. CONCLUSION

The dependence on stress of the water-retention of a needle-punched GCL was investigated by controlled suction oedometer measurements under constant confining stress. The suction was varied to determine the wetting path. To circumvent the capillary barrier effect of the carrier geotextile, the vapour-control technique was used. To obtain the two largest suctions (4.2 and 8.5 MPa), the standard technique of controlling relative humidity by using a saturated saline solution was used. For smaller suctions (0.1, 0.5, 1 and 2.8 MPa), the osmotic technique was adapted to control vapour by using calibrated concentrations of PEG solutions, ensuring a more continuous series of applied suctions along the wetting path, down to zero suction.

The experimental water-retention curves obtained under various confining stress allowed the following conclusions to be drawn:

- Increasing vertical stress resulted in a decrease in water uptake along the wetting path accompanied by a reduction in the swelling capacity and in the saturated hydraulic conductivity of the GCL.
- The WRCs obtained under the smallest stress (10 kPa) agree fairly well with existing WRCs of either GCLs or compacted bentonites used in radioactive-waste disposal. This results indicates that water retention in bentonites depend only slightly on their density, which is attributed to the predominance of physicochemical clay-water interactions.
- The WRCs obtained with the GCLs under stress also agreed with previously published WRCs for GCLs under stress.
- Examination of published data also reveals the significant effect of GCL structure on its ability to retain water.
- Two well-known formulas for WRCs (van Genuchten, 1985 and Fredlund and Xing, 1994) correctly fit the data obtained in this study. By fitting these equations to normalized water-retention curves, two new equations that include stress effects are proposed for WRCs. The corresponding surfaces are represented in three-

dimensional graphs that show the dependence of water content on stress and suction along a wetting path.

- The possible validity of the state-surface concept applied to GCLs under stress was discussed. The validity of this concept would likely be confirmed by constant-suction compression measurements on hydrated bentonites.
- Three-dimensional graphs that show the effects of stress on water retention in GCLs appear to be a useful way to illustrate the observed trends; namely, that water uptake is reduced in GCLs under larger stress.

The two new equations for volumetric water content of a GCL as a function of both suction and stress will certainly help hydromechanical numerical modeling of GCL hydration under specific site conditions, where GCLs are submitted to water infiltration under the weight of the supported waste layers. From a practical point of view, this study also emphasize on the recommendation of rapidly covering GCLs once they are installed so as to make them more rapidly operational and hydrated in barrier systems. In addition, immediately after GCL installation in geotechnical applications, a solid bonding structure is also recommended to naturally confine the GCL, even under low stress.

6. ACKNOWLEDGMENTS

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Table 1. Published investigations of GCL water-retention curves.

Authors	Used technique	Confining stress (kPa)	Water cycle
Daniel et al. (1993)	Thermocouple Psychrometer (SCM) and vapour equilibrium (MCM)	0	Wetting path
Southen and Rowe (2004)	Pressure plate technique (SCM)	0	Drying
Barroso et al. (2006b)	Filter Paper (MCM)	0	Wetting path
Southen and Rowe (2007)	Pressure plate (SCM) and pressure membrane extractors (SCM)	0-0.5-3-100	Drying path
Abuel Naga and Bouazza (2010)	Thermocouple psychrometer (MCM) and a Capacitive relative humidity sensor (MCM)r	50	Wetting path
Beddoe et al. (2010)	High-capacity tensiometers (MCM) and capacitive relative humidity sensors (MCM)	2	Drying path
Beddoe et al. (2011)	High-capacity tensiometers (MCM) and capacitive relative humidity sensors (MCM)	2	Wetting/Drying path
Henson et al. (2013)	Pressure plate-Filter paper and relative humidity methods	0	Wetting/Drying path

"SCM" stands for "suction-control method" and "MCM" stands for "moisture-control method."

Table 2 main features of the GCL studies

Materials	Properties	values
GCL	Thickness under 10 kPa EN ISO 9863-1 [m]	8×10^{-3}
	Mass per unit area EN 14196 [kg/m^2]	6.1
	Hydraulic conductivity NF P 84 705 under 10-160 kPa [m/s]	3.10×10^{-11} - 1.95×10^{-11}
	Bonding process	Needle punched
Cover geotextile	Type	Woven
	Mass per unit area EN 14196 [kg/m^2]	0.1
Benonite	Type	Granular sodium
	Mass per unit area EN 14196 [kg/m^2]	5.80
	Natural water content [%]	9.63
Carrier geotextile	Type	Non woven
	Mass per unit area EN 14196 [kg/m^2]	0.2

Table 3 Summary of measurements made to determine WRCs of GCLs.

Specimen	Method used	Controlled suction [MPa] [MPa]	Confining stress [kPa] [kPa]	Initial mass of GCL specimen [g] specimens
1	SS	8.5	10	23.09
2	SS	8.5	50	22.62
3	SS	8.5	200	22.29
4	SS	4.2	10	23.59
5	SS	4.2	10	23.64
6	SS	4.2	50	21.54
7	SS	4.2	200	25.3
8	PEG	2.8	10	24.57
9	PEG	2.8	50	23.02
10	PEG	2.8	200	22.54
11	PEG	1	10	23.82
12	PEG	1	50	23.94
13	PEG	1	50	24.51
14	PEG	1	100	22.65
15	PEG	1	200	23.97
16	PEG	0.5	10	22.99
17	PEG	0.5	10	23.89
18	PEG	0.5	50	22.52
19	PEG	0.5	100	22.41
20	PEG	0.5	200	23.34
21	PEG	0.1	10	24.52
22	PEG	0.1	50	23.09

23	PEG	0.1	100	24.47
24	PEG	0.1	200	22.70
25	PEG	0	10	24.12
26	OET	0	10	23.55
27	OET	0	50	24.68
28	PEG	0	50	23.05
29	OET	0	100	24.69
30	PEG	0	100	22.46
31	OET	0	200	22.99
32	PEG	0	200	21.43

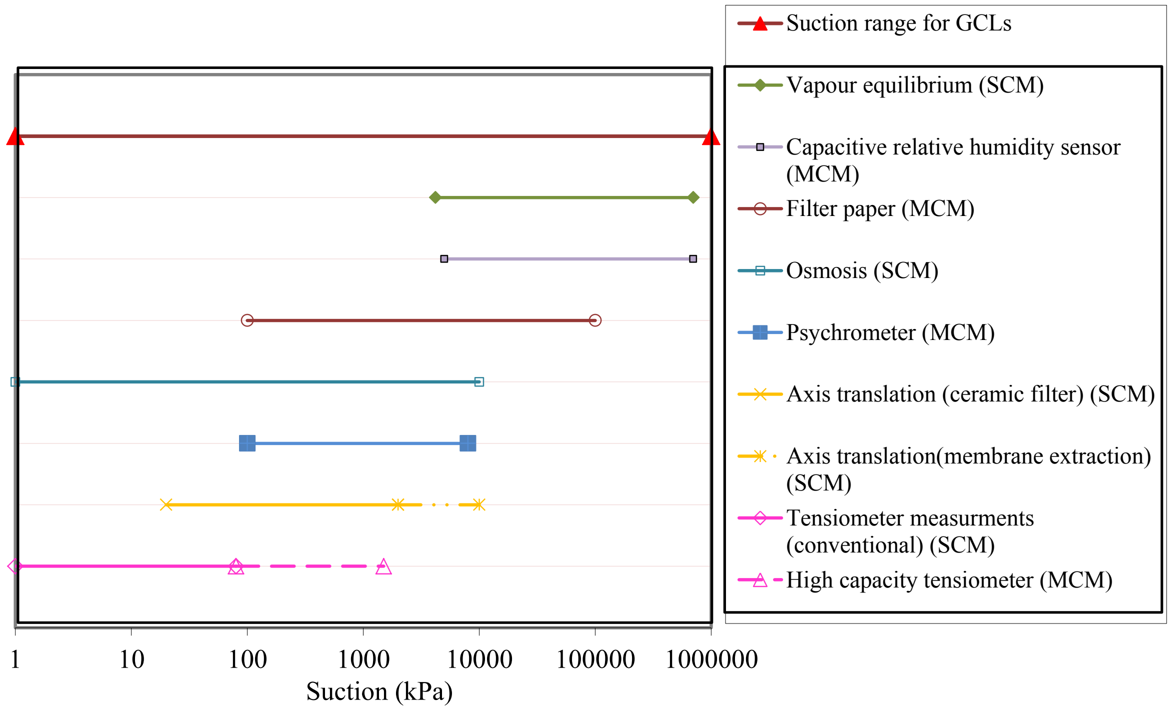
"SS" stands for the vapour-equilibrium technique by oversaturated saline solution. "OT" stands for "osmotic technique" and "OET" stands for "oedometric technique."

Table 4 Properties of salts used in this work (adapted from Delage et al., 1998).

Saturated salt solutions	Relative Humidity controlled [%]	Suction [MPa]	Solubility [g/l]	Molar mass [g mol^{-1}]
K_2SO_4	97	4.2	111	174.26
KNO_3	94	8.5	320	174.25

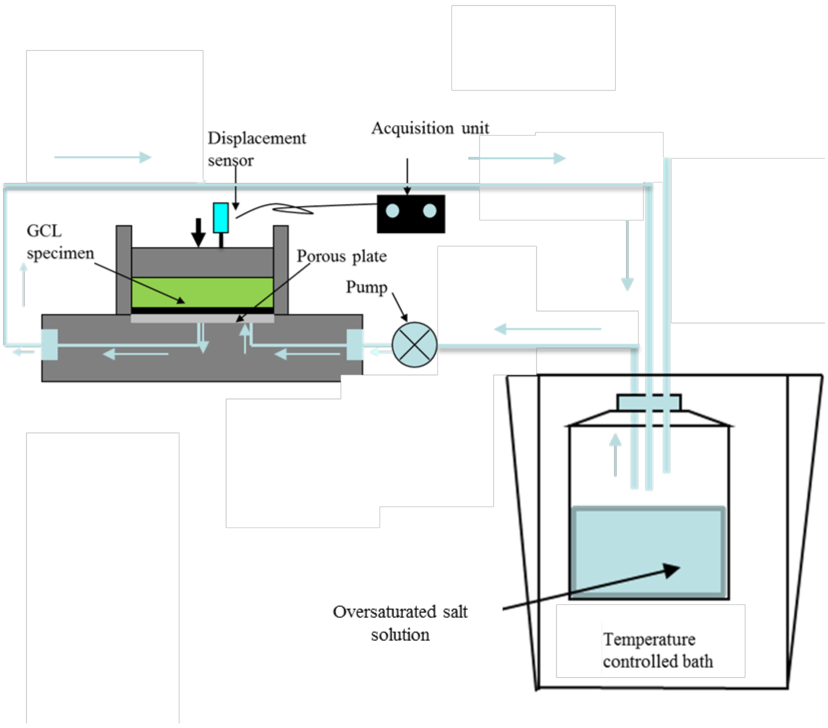
Table 5 Values of parameters obtained by fitting WRCs from Fig. 8 to Eqs. (4) and (5). Prior to fitting, WRCs were normalized to their water content at zero suction.

Model		Van Genuchten (1980)		Fredlund and Xing (1994)			
Fitting parameter	θ_s (m^3/m^3)	α (1/m)	n	a_f (kPa)	n_f	m_f	ψ_r (kPa)
10 kPa	0.97	0.16	1.35	100	0.73	1.10	3326
50 kPa	0.79						
100 kPa	0.71						
200 kPa	0.54						

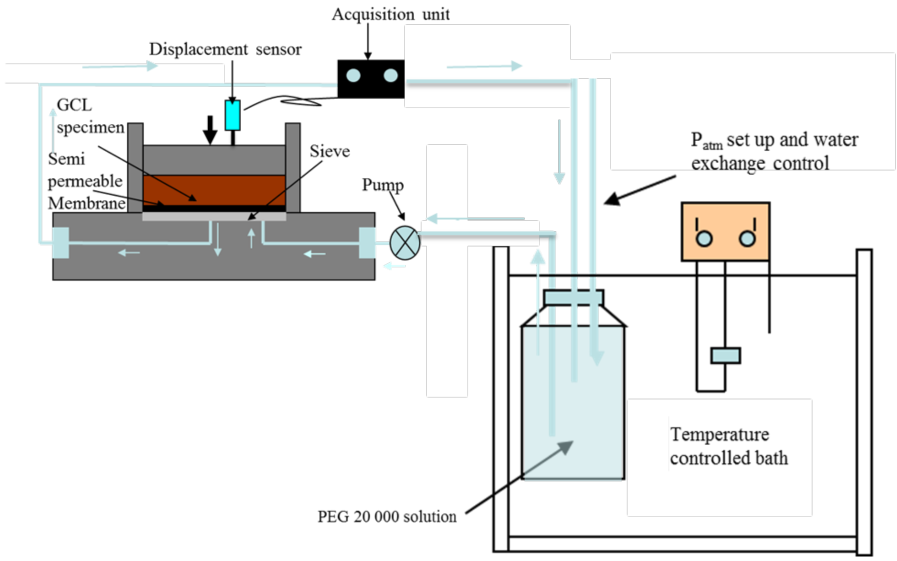


SCM: suction control method; MCM: moisture control method

Figure 1. Applicable ranges for techniques to control or measure suction (modified from Likos and Lu 2003).



(a)



(b)

Figure 2. Representations of methods used to control GCLs specimens' suction on oedometric cells (a) saturated salt solution by circulated vapour. (b) Osmotic technique with circulated PEG solutions (adapted from Delage and Cui, 2008).

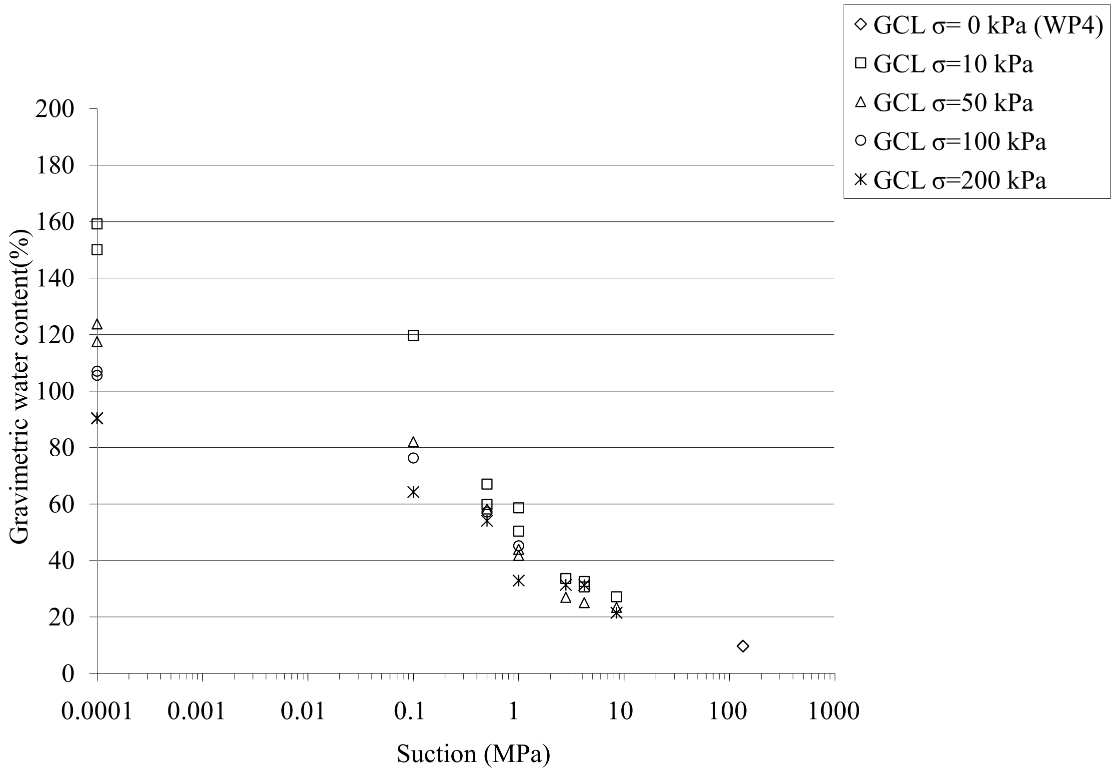
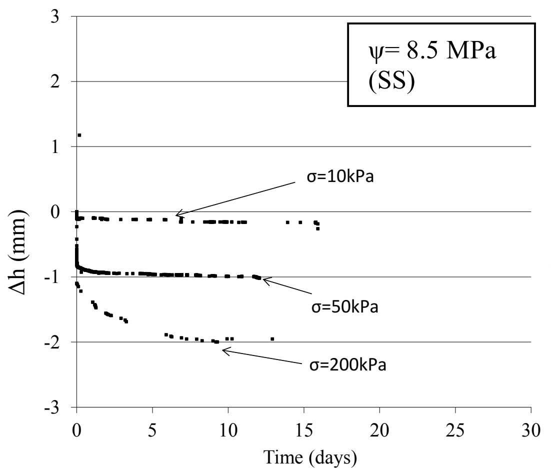
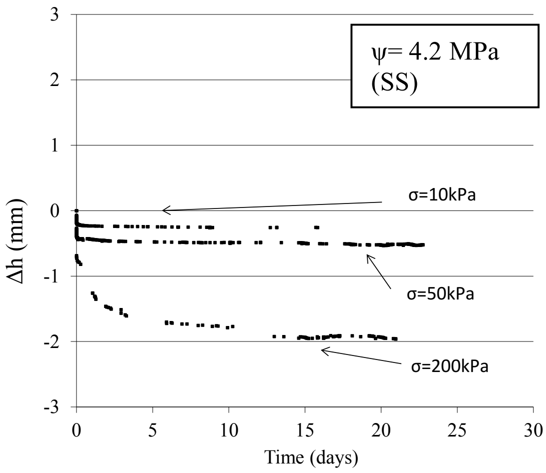
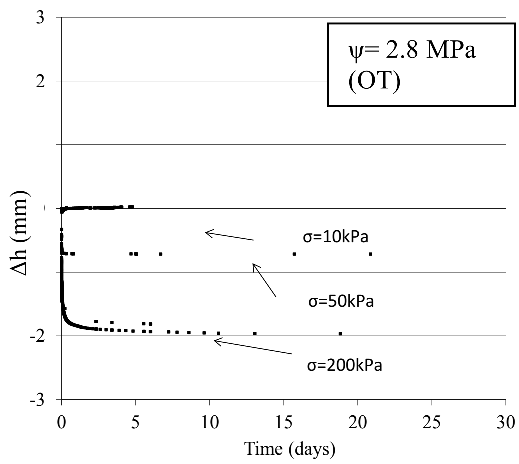


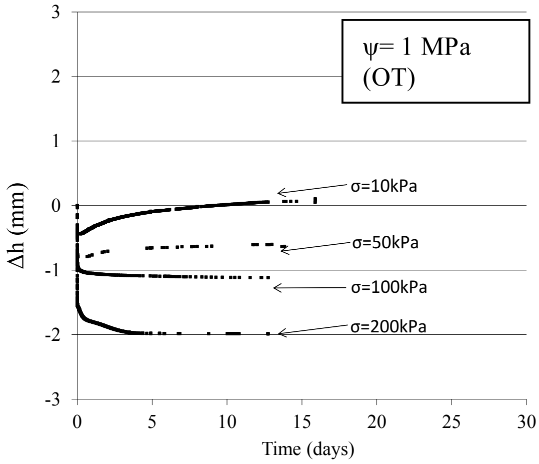
Figure 3. Water retention along the wetting path under vertical stresses of 10, 50, 100, and 200 kPa.


ψ= 8.5 MPa (SS)
σ=10kPa
σ=50kPa
σ=200kPa
Δh (mm)
Time (days)

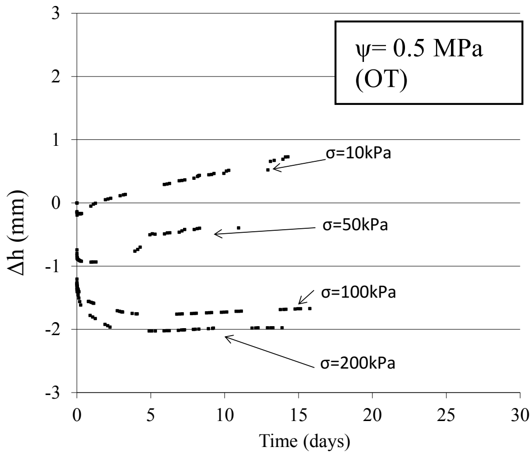

ψ= 4.2 MPa (SS)
σ=10kPa
σ=50kPa
σ=200kPa
Δh (mm)
Time (days)

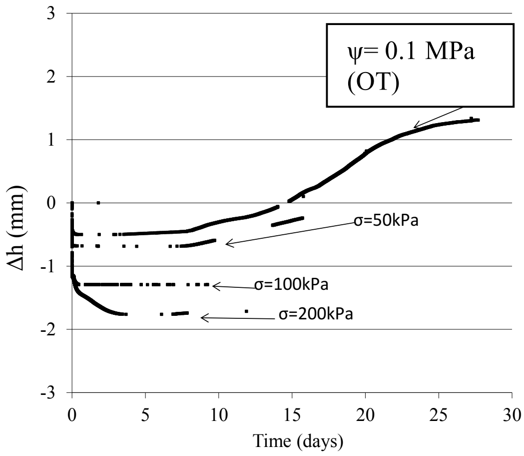
(a) (b)


ψ= 2.8 MPa (OT)
σ=10kPa
σ=50kPa
σ=200kPa
Δh (mm)
Time (days)

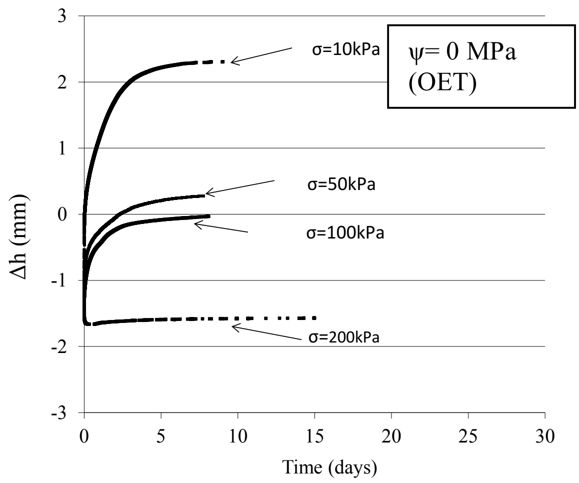

ψ= 1 MPa (OT)
σ=10kPa
σ=50kPa
σ=100kPa
σ=200kPa
Δh (mm)
Time (days)

(c) (d)


ψ= 0.5 MPa (OT)
σ=10kPa
σ=50kPa
σ=100kPa
σ=200kPa
Δh (mm)
Time (days)


ψ= 0.1 MPa (OT)
σ=50kPa
σ=100kPa
σ=200kPa
Δh (mm)
Time (days)

(e) (f)



(g)

Figure 4. Change in Thickness of GCL specimens as a function of time for different confining stresses σ and for final suctions reached starting from initial suction of 135 MPa.

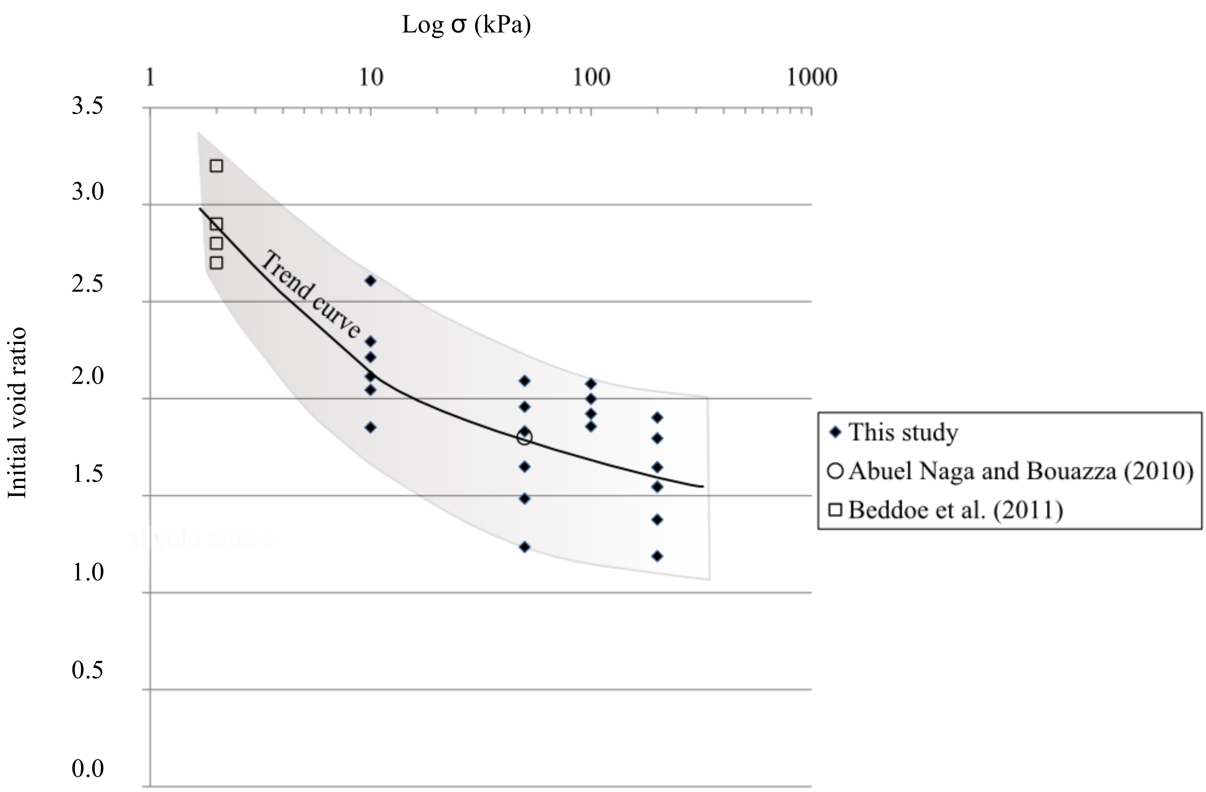


Figure 5. Initial void ratio as a function of the logarithm of the stress for dry GCLs (data from all measurements) compared to published data.

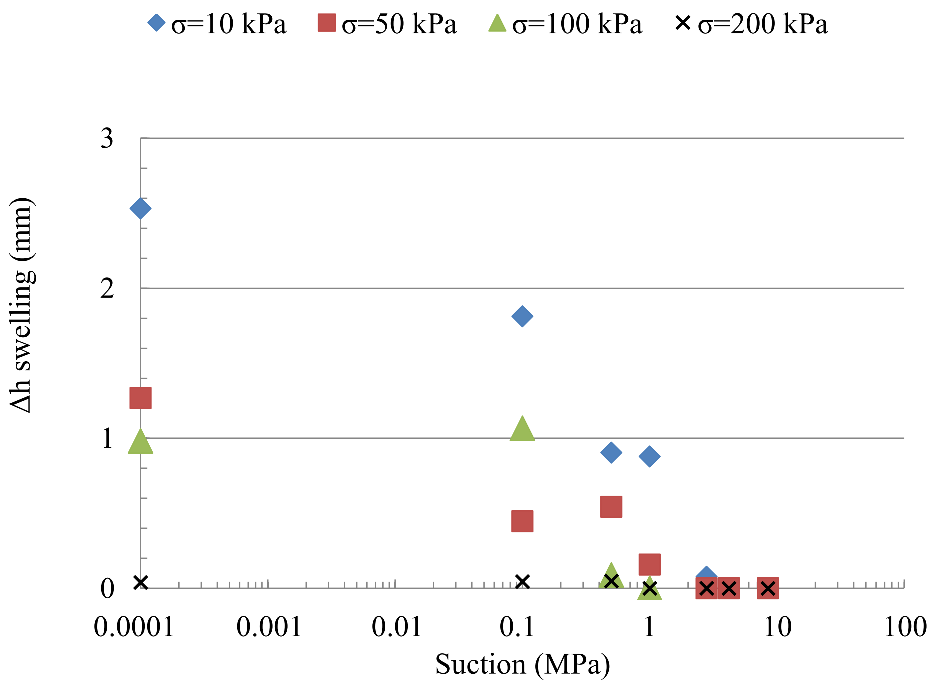


Figure 6 Comparaison of changing height between GCLs specimens with suction as a function of confining stress

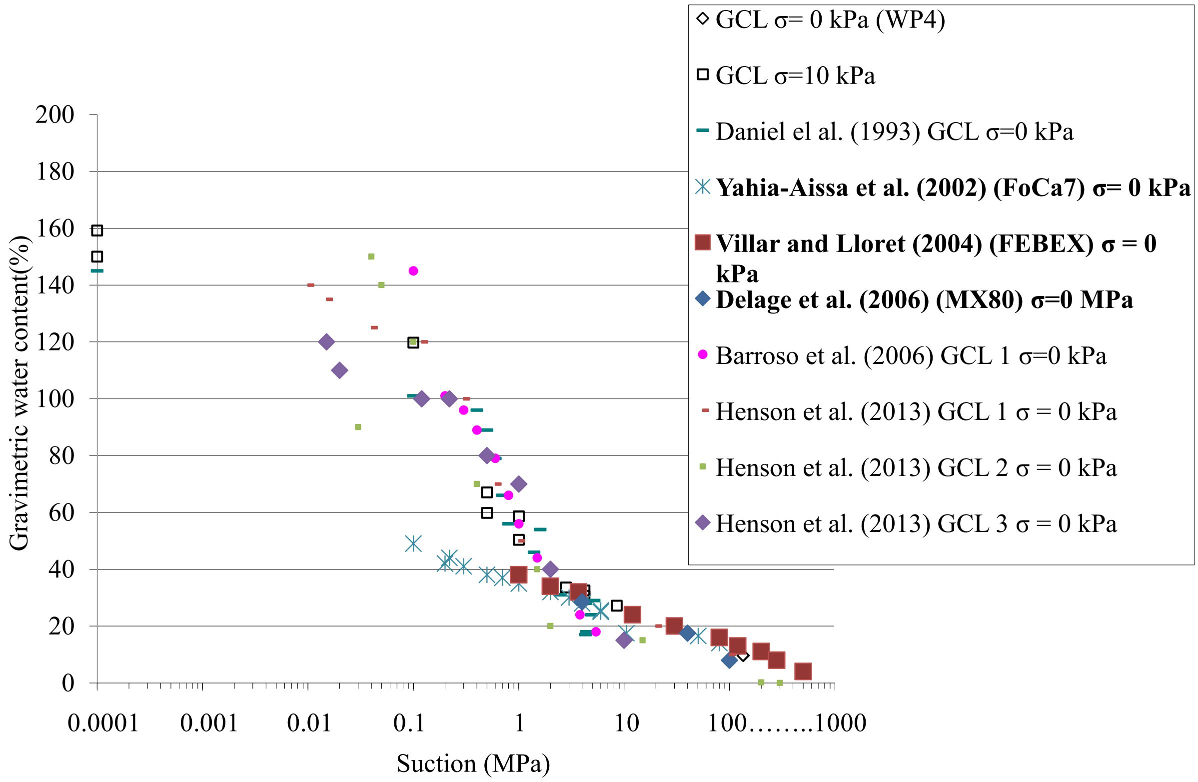


Figure 7. Comparison of wetting path water-retention data obtained in present study with published results for GCLs and bentonites (deeply-buried). All data were acquired under free-swell conditions.

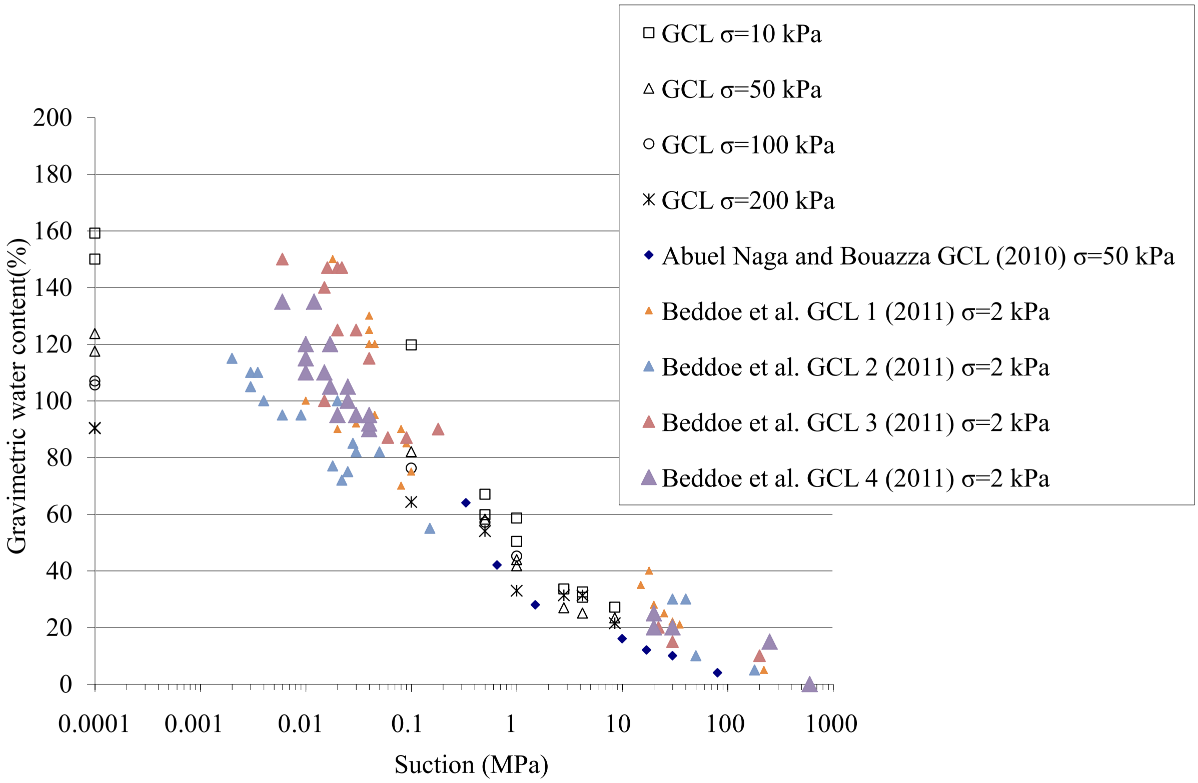
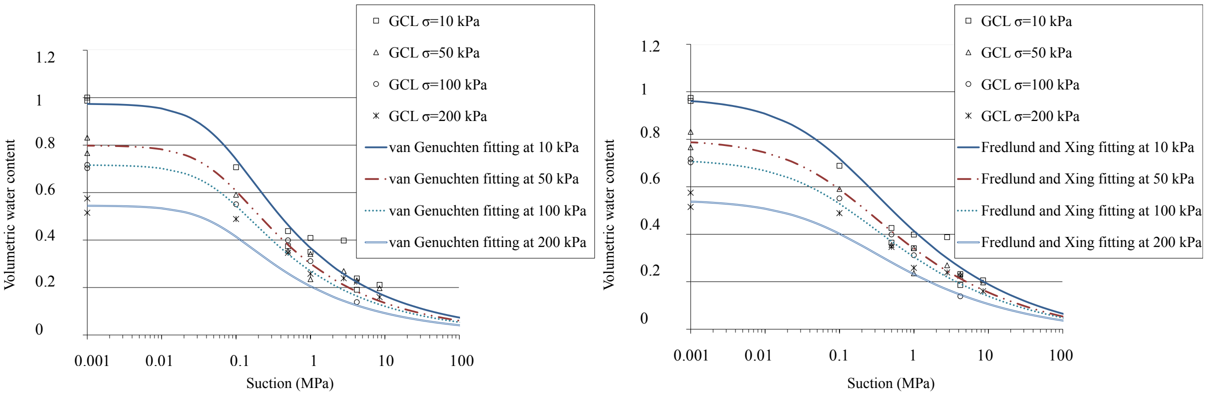


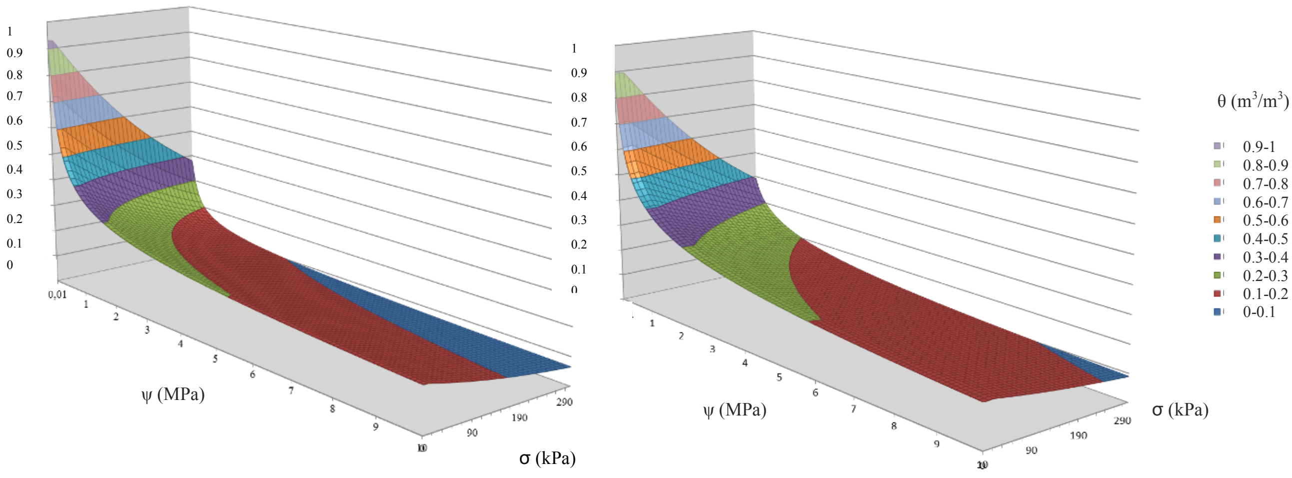
Figure 8 Wetting path water-retention data obtained in the present study compared with published results. All data were acquired with GCLs under nonzero confining stress.



(a) (b)

Figure 9. Fits to experimentally determined WRCs at various vertical stresses using (a) van Genuchten's equation (4) and (b) Fredlund and Xing's equation (5).

θ (m^3/m^3) θ (m^3/m^3)



(a) (b)

Figure 10 Dependence of WRCs on stress σ for GCL [$\theta = f(\psi,\sigma)$] based on (a) van Genuchten equation (4) and (b) on Fredlund and Xing equation (5).