Role of the Soil Mineralogy on the Temperature Dependence of the Water Retention Curve

Bertrand François and Sana Ettahiri

Abstract. This paper presents experimental results of water retention curves of a compacted clay silt at different temperature. For limited suction values (up to 220 kPa), the results show a significant effect of the temperature variation (from 22°C to 50°C) on the water content at constant suction. This effect cannot be exclusively attributed to the thermal decrease of the surface tension of water. Through this study, the thermal decrease of the thickness of the diffuse double layer around the clay particles is assumed to be the most significant effect that explains the decrease of water retention capability when temperature increases. With this approach, the temperature effect on the water retention curve of any clayey soil can be estimated from the mineralogical composition of the soil. This theory is applied on five different clayey soils.

Keywords: degree of saturation, suction, temperature, diffuse double layer.

1 Introduction

The recent developments in the field of unsaturated soils have underlined the key role of the water retention curve on the mechanical behaviour of an unsaturated soil. So, it is essential to quantify the amount of water stored in an unsaturated soil as a function, not only of the suction, but also of additional environmental parameters (Gallipolli et al. 2003, Nuth & Laloui 2008, François & Laloui 2008).

   Two main effects may significantly modify the water retention curve of a soil: the deformation and the temperature. The effect of soil deformation on the water

Bertrand François
Université Libre de Bruxelles, Brussels, Belgium
e-mail: bertrand.francois@ulb.ac.be

Sana Ettahiri
Université Libre de Bruxelles, Brussels, Belgium
e-mail: sana.ettahiri@ulb.ac.be

retention curve is mainly related, at the micro-scale, to the change in the dimensions of voids. The smaller the pores, the higher the suction that the capillary meniscus can sustain before air enters the pores. The effect of temperature on the water retention curve is more complex. It is the consequence of several physical mechanisms that act at the particle scale. These phenomena are related to the role of temperature on the capillary mechanisms, on the short-range solid-liquid interaction or on the phase change mechanisms (Romero et al. 2003). This paper focuses exclusively on this thermal influence on the water retention curve. It is suggested, and demonstrated, that the main thermal effect is probably related to the evolution of the thickness of the diffuse double layer with temperature.

2   Experimental Results

A series of water retention curves of a compacted clay silt have been obtained at three different temperatures (22°C, 35°C and 50°C) with pressure plate apparatus. The tested soil is a clayey silt (classification USCS: CL-ML) from the region of Namur in Belgium, called Marches-les-Dames (MLD). Its index properties are: w_L=28.4%, I_P= 8.8%. The clayey fraction represents 23%, the silty one 67% and the sandy one 10%. The samples have been compacted upon the optimum standard Proctor conditions $\gamma_{d,opt}$ = 18.4 kN/m^3 and w_{opt} = 14.8%. After resaturation with a low positive water pressure (10 kPa), the pressure plate apparatus have been placed in temperature-controlled chambers regulated at 22°C, 35°C and 50°C. Suction has been applied step by step until a suction of 400 kPa.

Fig. 1 represents the obtained water retention curve in terms of water content as a function of the applied suction. For the limited suction values applied in this experimental program, the results show a significant effect of the temperature variation on the degree of saturation at constant suction. The experimental points are fitted with the analytical expression of Van Genuchten (1980).
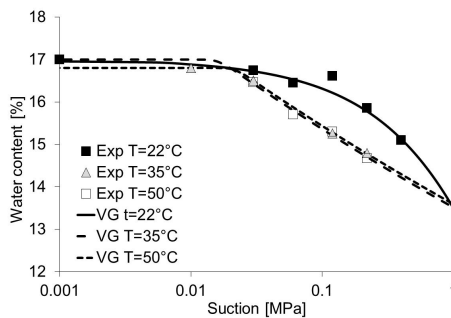

Fig. 1. Water retention curve of the compacted MLD clayey silt obtained at 22, 35 and 50°C. Fitting with the expression of Van Genuchten (1980) (VG).

3 Thermal Degradation of Water Retention Capacity

The retention capability of a soil, at a micro-scale, results from the equilibrium between stresses in fluid phases, capillary forces acting at the interface of each phase and attractive forces between water and particles. A change of temperature induces a modification of the properties of the different phases and also of their interfaces. Some thermal effects will dissipate with time by means of the diffusion of fluid phases (short term effects), while other effects directly affect the intrinsic properties of materials and are not dampened with time (long term effects), except if the temperature recovers its initial value (François 2008).

First, because water dilates more than the solid skeleton, water phase occupies proportionally more pore space when temperature increases. However, this effect is dampened with time when a new equilibrium is reached after diffusion of the excess of water in the voids. Also, during soil heating, the thermal decrease of the solubility of air in water produces the release of a quantity of air from water. Consequently, it may decrease the proportion of water in the voids. However, through air diffusion, this effect can also dissipate with time.

A well-known effect is related to the thermal decrease of the surface tension between air and water phases. Through the Young-Laplace equation, the decrease of surface water-air tension with temperature decreases the radius of the meniscus. As a consequence, some pores which were water-filled at ambient temperature can be drained at elevate temperature. It causes the degree of saturation to decrease.

Finally, in clayey soils, water can also be stored in the diffuse double layer of the clay platelets. In that zone, the cations of water are strongly attracted by the particle. The thickness of this diffuse double layer is affected by temperature. Mitchell (1976) defined a quantity that is a good approximation of the measure of the thickness of the double layer. This quantity is proportional to the square root of "the dielectric constant (D) of water multiplied by the temperature (T) in Kelvin". When temperature increases, the product $D \times T$ drops which induces a degradation of the diffuse double layer. So, the retention capability of water in the vicinity of the clay platelet decreases with temperature.

Table 1 summarize the quantification of the four main thermal effects in terms of the degree of saturation decrease for a temperature variation from 0°C to 60°C.

4 Applications

In this section, the focus is on the thermal degradation of the diffuse double layer. To do so, there are several uncertainties that need to be approximated. Indeed, the objective of this study is not to bring a rigorous quantitative approach, but rather to give a qualitative proof that the thermal degradation of the double layer is probably the most significant effect that explains the decrease of the retention capability of soils with temperature (as already suggested by Table 1). At that scale of the problem, the amount of water stored in the diffuse double layers depends on the

thickness of the diffuse layer and the specific surface of the soil. The thickness of the diffuse layer depends on many parameters of the solution and of the clay mineral (Mitchell 1976). At ambient temperature and for usual electrolyte concentration in water, a thickness of 60 Å is a good approximation. The specific surface of the soil particles can be obtained as a function of the mineralogy of the clay. Table 2 summarizes the specific surface of the main clay minerals.

Table 1. Quantification of the different thermal effects on the evolution of the degree of saturation at constant suction (François 2008).

Thermal effect	Variation of S_r for a ΔT from 0°C to 60°C
Thermal dilation (Short term)	$\Delta Sr = 2.16 \%$
Air solubility in water (Short term)	$\Delta Sr = 1.24 \%$
Surface tension of water (Long term)	$\Delta Sr = 1$ to 3% depending on the pore size distribution of the material.
Diffuse double layer (Long term)	$\Delta Sr = 4 \%$ if all the water is included in the diffuse double layer

Table 2. External specific surface of the main clay minerals (Morel 1996).

Clay mineral	External specific surface [m²/g]	
	Range of variation	Average value
Illite	80-120	100
Vermiculite	40-70	57.5
Kaolinite	10-30	20
Chlorite	100-175	137.5
Montmorillonite	80	80

The water content stored in the diffuse double layer is:

$$w_{DDL} = \left(\sum_i p_i SS_i \right) t_{DDL} \rho_w \tag{1}$$

where p_i and SS_i are, respectively, the mass proportion and the specific surface of the clay mineral i. t_{DDL} is the thickness of the diffuse double layer (assumed $= 60$ Å $= 6.10^{-9}$ m) and ρ_w is the bulk density of water ($=10^6$ g/m³).

The total variation of the water content dw with temperature changes dT can be considered by the sum of the effects of the variation of surface tension $d\sigma_s$ of air/water interface (as deduced analytically by Salager et al. 2010) and the evolution of the thickness of the double layer (linked to the square root of DxT), the second effect being the most significant in clay:

$$dw = dw_{\sigma_s} + dw_{DDL} = -\frac{s}{F_w \sigma_s} \frac{d\sigma_s}{dT} dT + \left(\sum_i p_i SS_i \right) \rho_w t_{DDL} \frac{d\left((DT)^{1/2} \right)}{dT} dT \tag{2}$$

Table 3. Clay mineralogy of the different soils addressed in the next part.

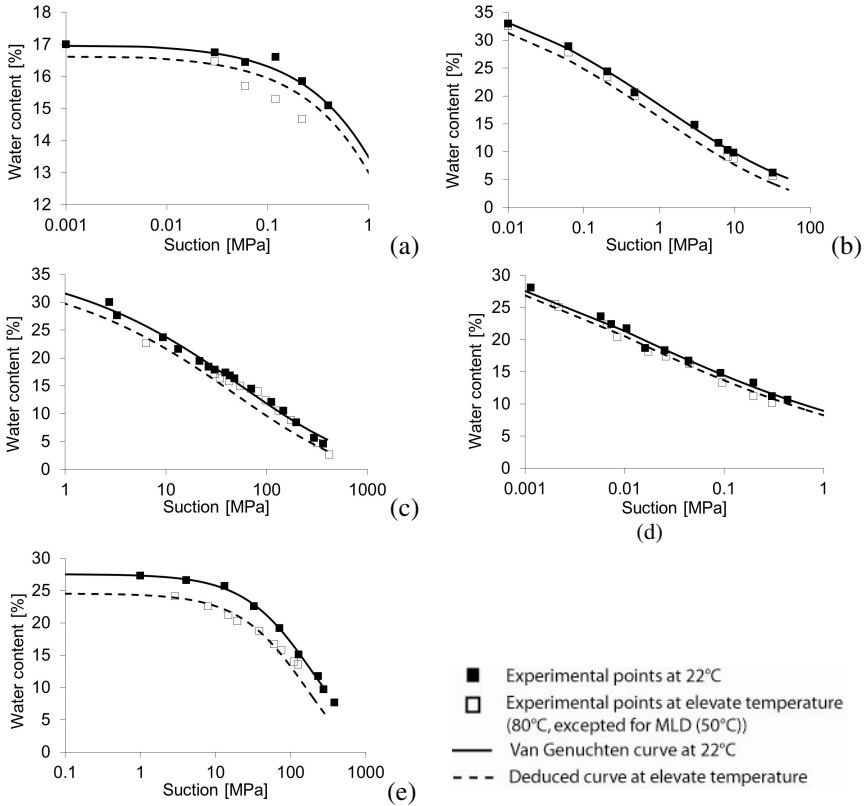|	Soil	Authors	Clay mineralogy
(a)	MLD (clayey silt)	This study	Illite: 12%; Vermiculite: 9%; Kaolinite: 4 %
(b)	Boom Clay	Romero et al. (2003)	Kaolinite: 29% ; Smectite: 22% ; Illite: 19%
(c)	FoCa Clay	Imbert et al. (2005)	Kaolinite: 42% ;Beidellite: 38% (≈ Smectite)
(d)	Clayey silty sand	Salager et al. (2010)	Smectite: 5% ; Chlorite: 5%
(e)	FEBEX Bentonite	Villar & Lloret (2004)	Smectite: 92%

Fig. 2. Application of the proposed relation to deduce the effect of temperature on the water retention curve. The dashed line is deduced from the full line by equation (2). Experimental points: (a) MLD, (b) Boom Clay, (c) FoCa Clay, (d) Clayey silty sand, (e) FEBEX bentonite.

where F_w is the derivative of the matric suction as a function of w. In the following, Equation (2) is tested on five different soils, the mineralogical compositions of which are reported in Table 3.

In Fig. 2, the obtained results at ambient temperature have been fitted with the Van Genuchten analytical expression. Then, from equation (2), the curve at

elevate temperature has been obtained. It reveals the very good agreement between the theoretical development and the experimental observations. The soils having the larger specific surface exhibit a stronger thermal effect on their water retention curve. In particular, the FEBEX bentonite (Fig. 2e) shows a decrease of the water content of about 4% upon heating up to 80°C at constant suction. On the contrary, the clayey silty sand (Fig 2d), having a low specific surface; shows a limited effect of temperature on the water retention curve.

5 Conclusions

The thermal decrease of the water retention capacity of soils is usually explained by the temperature-dependence of the surface tension of water. However, in clayey soil, this is probably not the most significant effect. The role of the temperature on the thickness of the diffuse double layer surrounding the clayey platelets is probably predominant. This thickness decreases of about 4% when temperature increases from 20°C to 80°C. It may seem insignificant but when the most part of the pore water is included in the diffuse double layer (as it is the case in dense clay), this is the main mechanism that explains the loss of water upon heating at constant suction. This hypothesis has been verified by applying it on five different soils for which water retention curves at two temperatures were available. Also, a new series of experimental curves have been obtained on a compacted clayey silt at three temperatures that confirms the suspected phenomenon.

References

Gallipoli, D., Wheeler, S.J., Karstunen, M.: Modelling the variation of degree of saturation in a deformable unsaturated soil. Géotechnique 53(1), 105–112 (2003)

François, B.: Thermo-plasticity of fine-grained soils at various saturation states: Application to nuclear waste disposal. PhD Thesis No. 4188, EPFL, Lausanne (2008)

François, B., Laloui, L.: ACMEG-TS: A constitutive model for unsaturated soils under non-isothermal conditions. Int. J. Num. Anal. Meth. Geomech. 32, 1955–1988 (2008)

Imbert, C., Olchitzky, E., Lassabatère, T., Dangla, P., Courtois, A.: Evaluation of a thermal criterion for an engineered barrier system. Engineering Geology 81, 269–283 (2005)

Mitchell, J.: Fundamentals of Soil Behavior. Wiley (1976)

Morel, R.: Les sols cultivés. Lavoisier, Paris (1996)

Nuth, M., Laloui, L.: Advances in modelling hysteretic water retention curve in deformable soils. Computers and Geotechnics 35(6), 835–844 (2008)

Romero, E., Gens, A., Lloret, A.: Suction effects on a compacted clay under non-isothermal conditions. Géotechnique 53(1), 65–81 (2003)

Salager, S., El Youssoufi, M.S., Saix, C.: Effect of temperature on water retention phenomena in deformable soils: theoretical and experimental aspects. European J. Soil Sc. 61, 97–107 (2010)

van Genuchten, M.T.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898 (1980)

Villar, M., Lloret, A.: Influence of temperature on the hydro-mechanical behaviour of a compacted bentonite. Applied Clay Sciences 26, 337–350 (2004)