

State Paths of Clay Dominated Soils of Coastal Marshland: Scale Effect and Hydrodynamic Behaviour

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Abstract. The paper is focused on clayey dominated sediments of coastal marshes of the West Atlantic coast of France because of their homogeneity in texture and mineralogy, and their vertical structure evolution from dried and solid state in surface down to saturated plastic-to-liquid state in depth. It proposes a "review" of the complementary petrographic and hydro-mechanical data obtained on these clay dominated soils and a method of calculation for the relationships prevailing between the hydro-mechanical properties and microstructure behaviour of the clay matrices. This tool, based on the shrinkage curve of the clay matrix is applied as aid to the hydraulic management of marshlands regarding the soil-plant interactions.

1. Introduction

The state paths of clay dominated matrices govern their behaviour regarding the soil geotechnical to soil agronomic potential. On a mechanical point of view, the soil abilities can be followed, in laboratory, along the compressibility line and/or shear stress "lines" according to oedometric and /or triaxial tests performed on clay matrix samples. In situ, the soil characteristics are logged via drill holes and associated measurements obtained using penetrometer, pressiometer and/or SPT type investigations. In fact, the "compressibility" parameters are mainly controlled by the hydraulic conductivity of the clay matrices [1]. For soils, regarding the agronomic potential, the objectives are to optimize the soil - plant interactions. In fact, the microstructure - hydro-mechanical property relationships govern the water transfers and the soil behaviours from the metric to decametric scale of the agricultural plots to the infra-millimetre scale of the root/clay matrix interfaces.

The fundamental parameter which must be calculated are the AWC (Available Water Capacity) and PAW (Plant Available Water) [2, 3]. Eventually, two dominant questions exist: how to change of scale from the clay matrix microtexture to soil behaviour calculation and modelling? and how to compare the state paths for compression and desiccation stresses. Biarez et al. (1987) [4] demonstrated the similarity between the compressive and desiccation paths via the comparison between compressive stress and suction pressures. Dudoignon et al. (2004) [1] quantified the relationship existing between the state paths of clay-matrices and particle rearrangement during triaxial tests. The authors established relationship between Cam-Clay and hydraulic conductivity diagrams applying the Kozeny-Carman equation to clay-matrix microstructures quantitatively analysed by microscope image analysis (Figure 1).



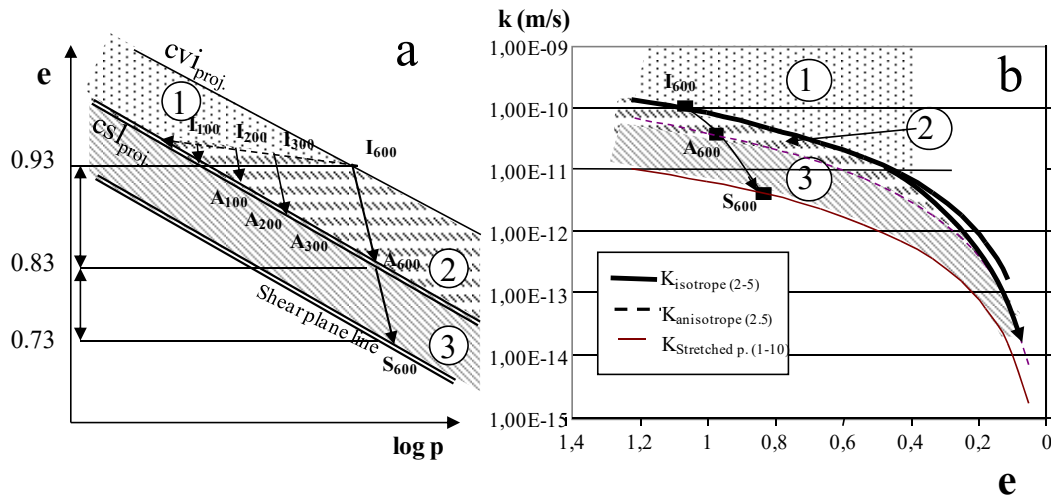


Figure 1. State paths of kaolinite matrices during triaxial shearing tests in Cam-Clay diagram and Kozeny-Carman hydraulic conductivity (k) diagram. e = void ratio, p = average pressure, (2-5) and (1-10) are the particle shape factors used to the tortuosity calculation.

In fact, both for the compressive and desiccation stresses, the state paths of soil are mainly controlled by the couple particle rearrangement - water transfer functions.

2. Materials and Methods

The studied marsh soils are located in the Marais Poitevin and Marais de Rochefort (Figure 2). The successive relationships between the clay matrix structures and their hydro-mechanical properties were equated from data mainly acquired in the experimental site of INRA (French National Institute of Agronomic Research) of Saint Laurent de la Prée (Charente- Maritime department, France; Figure 2a; [5, 6, 7, 8]). The soils result from the reclaiming of the primary wetlands by hydraulic managements began since the Middle Ages. The sediment state evolution has been the consequence of compaction and maturation of the primary mud deposited since the Flandrian regression. The sediment is characterized by a fine-grained texture (85-to-92% of particles $< 20 \mu\text{m}$) and small organic matter content (0.4 to 2.4%). The Cationic Exchange Capacity accords to the “illite domain (20-30 meq/100g). The mineralogy of the clay assemblage is composed of dominant illite plus kaolinite and illite/smectite mixed layers and very small amount of pure smectite [9, 7]. The vertical water profiles are governed by the groundwater nape level induced by the chronicle of the hydraulic managements; i.e. polder since the Middle Ages and drainage since the 1970's. The objectives have always been the desaturation and desalinization of soil surface being attentive to the water and salt stress for plants. The control may be ensured by W (water content) and $CE_{1/5}$ (electrical conductivity 1:5) profile monitoring [8, 2]. The final results have to be given in AWC, PAW profiles, salinity profiles and eventually crop yields.

The relationships between the structure and hydro-mechanical properties of the clay dominated material were based on the parallel between the shrinkage curve and the vertical water content profiles. The shrinkage (W_r), plastic (W_p) and liquidity (W_l) limits of the material are 20, 40 and 70% respectively. The in situ hydro-mechanical profiles which were recorded included gravimetric water content (W) and wet density (γ_w) measured on hand auger samples taken every ten centimetres at least to 2.00 m depth, cone resistance (Q_d) by PANDA dynamic penetrometer and shear strength (C). The W measurements were associated to, 1/5 soil electrical conductivity ($CE_{1/5}$). The investigations were completed by electrical tomography (Syscal R1+ interfaced with a switch connected to 48 electrodes). Thus, the Archie's law was calibrated using the method of penetrometer + salinometer coupling in order to measure real resistivity for real depths [6]. The hydraulic conductivity of the clay matrix at

successive stage of consolidation was measured via oedometric compressibility tests on intact matrices sampled around 2.00 m depth and initially nearby the Wl state. The measured hydraulic conductivities have been compared to those calculated according to the microstructure state paths and Kozeny-Carman equations [1].

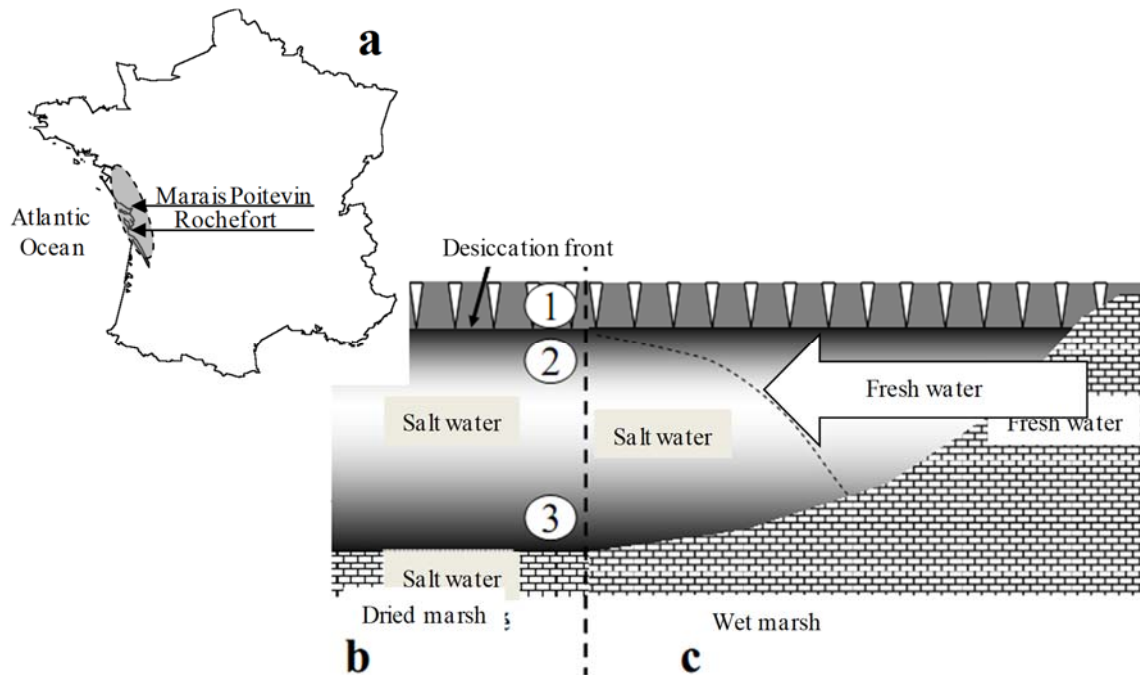


Figure 2. a- Location of the investigation sites along the West Atlantic coast of France (Marais de Rochefort and Marais Poitevin). b & c vertical evolution of the clay dominated sediments from the solid state in surface (1) to the plastic-to-liquid state (2) caused by the desiccation phenomenon and (3) liquid-to-plastic state in depth due to the earth weight consolidation effect. The sediments are saturated by fossil salt water in the dried marsh whereas fresh water inlets from the peripheral limestone hills in the wet marsh (from Gallier *et al.*, 2012 [8]).

Regarding the soil - pedodiversity and crop yields relationships, the W and $CE_{1/5}$ profiles were used for the calculation of AWC and PAW behaviour through the seasons [2]. The objective was to confront the plant growing and crop yields (grassland and cereal culture) to the water and salt stress profiles. In fact, the fluctuation of groundwater nape allows the desalinisation of surface, and the W profile patterns via the competition between the down progression of the desiccation front and up progression of the capillarity front from the groundwater "piezometric" level.

3. Results and discussions

From the surface down to 2.00 m depth the vertical soil to- sediment structure is governed by the down progression of the desiccation front. Thus a two-layer structure is developed (Figure 2b, c): the W_s - W_p solid state layer in surface, affected by the shrinkage phenomenon and associated shrinkages cracks, and the W_p - W_l subjacent plastic-to-liquid state layer characterized by hydraulic conductivities only governed by the clay matrix microstructure. The shrinkage curve has been obtained by drying unremoulded samples at initial water contents nearby the liquidity limit to the full desiccation at 105°C. Bernard *et al.* (2007) [5] demonstrated that the shrinkage is isotropic in the W_s - W_p domain and characterized by a simple shrinkage line as follows:

$$e = 2.58 W \text{ with } 2.58 \text{ g/cm}^3 = \text{average particle density.} \quad (1)$$

In fact, in the 50 - 90% W domain, the shrinkage curve presents a weak curvature. Nevertheless, it can be modelled by a Cornelis equation as follows [8]:

$$e = e_0 + \gamma (\exp(-\xi/\zeta)) , \text{ with } e_0 = 0.55, \gamma = 11.59, \xi = 1.78, \zeta = 0.63. \quad (2)$$

The parallel between the vertical W profiles and the shrinkage curve allows equating the mechanical resistances, hydraulic conductivity or other hydro-mechanical parameters according to the void ratio (e) or the gravimetric water content (W) (Figure 3). The C-e and Qd-e (or C-W, Qd-W) relationships have been equated by Perdok modified equations and power law equations [6, 8]. The Perdok equations need to fit four a_0 , a_1 , a_2 and a_3 coefficients:

$$\log(R) = a_0 + a_1 \frac{e}{1+e} + W(a_2 + a_3 \frac{e}{1+e}) \quad (3)$$

with $R = Qd$ or C .

The power law equation is easier to use which only A and b coefficients to fit:

$$R = (e/A)^{1/b} \text{ or } R = (\gamma s W/A)^{1/b} \quad (4)$$

All the profiles have been recorded regarding the agronomic objectives. Thus they have been performed in grasslands and in cereal culture fields. The shrinkage curve - Qd and C relationships are applicable for unfractured clay matrices. Thus they have been calculated after deleting the surface artefacts caused by the tillage. The Archie's equation has also been calibrated via double penetrometer plus salinometer investigations, and then verified regarding the clay dominated nature of the material according to Waxman & Smits (1968) [10] [6, 8]:

$$\rho_s = 1.01 \rho_f \phi^{-2.73} Sat^{-2} \quad (5)$$

with ρ_f = water resistivity, ϕ = porosity, Sat = saturation index.

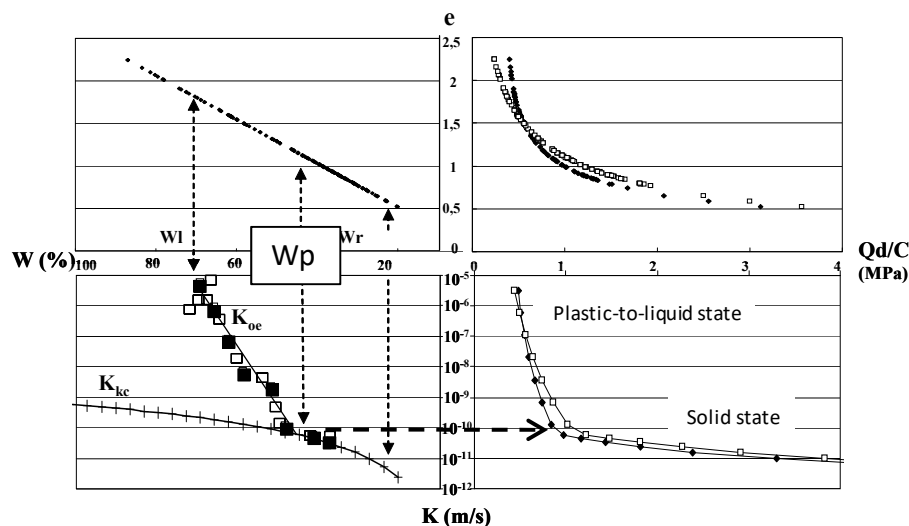


Figure 3. Example of W-e-Qd/C-K crossed diagram representation of the soil profiles. K_{kc} = Kozeny-Carman hydraulic conductivity, K_{oe} = oedometer conductivity hydraulic. The e - Qd/C curves are the average power laws characteristic of the desiccation profiles. W_p clearly separates the two hydrodynamic domains: i.e. solid and plastic state [8]

The AWC is usually calculated according to the soil texture and/or the rainfall-evapotranspiration balances. It is a quite constant "surface" value calculated as follows:

$$AWC = h \times d (W_{fc} - W_{wp}) \times 10 \quad (6)$$

with h the thickness of soil (in m), d the apparent density, W_{fc} the field capacity quite equivalent to 30%, W_{wp} the wilting point quite equivalent in our territories to the shrinkage limit (W_s) [2]. On the contrary the PAW is governed by the rainfall, the water plant consumption, and the kinetics of clay matrices microstructure evolution. The PAW can be calculated using tensiometric profiles [3]. Unfortunately, the clay dominated soils are particularly sensitive to the shrinkage phenomenon and do not allow continuous recording of tensiometric pressures because of the shrinkage crack propagations and disconnection of porous plugs (Figure 5). In these conditions, each PAW profile has been calculated for the successive dates by replacement of W_{fc} by the water content measured for each date at successive depths in equation 7 (Figure 4).

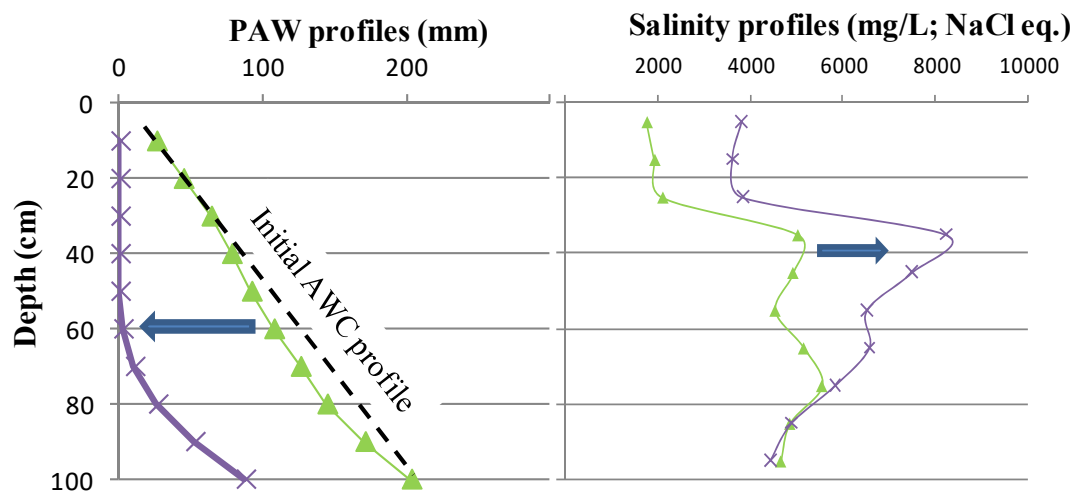


Figure 4. The PAW and associated salinity profile evolution from May to July in a cereal field clearly shows the superimposition of the water and salt stresses according to the successive steps of plant growth

In fact, the tensiometric data recorded through the seasons can be linked to the microstructure of the clay matrix, not only via the Jurin law regarding the pore size evolution, but also via the W-e-C diagram to explain the down progression of the shrinkage cracks (Figure 5).

4. Conclusions

Taking the shrinkage curve as reference allows the representation of the clay matrix microstructure behavior in such W-e-C-K crossed diagram whether for vertical profile or for a root environment. The main condition is to have a void ratio or porosity quantification. In comparison with geotechnics the soil surface evolution is mainly governed by the desiccation phenomenon locally supplemented with settlement provoked by the cattle trampling and/or farming engines. The method may be used as a tool for the hydraulic management of these territories regarding the soil - plant interaction and crop yields.

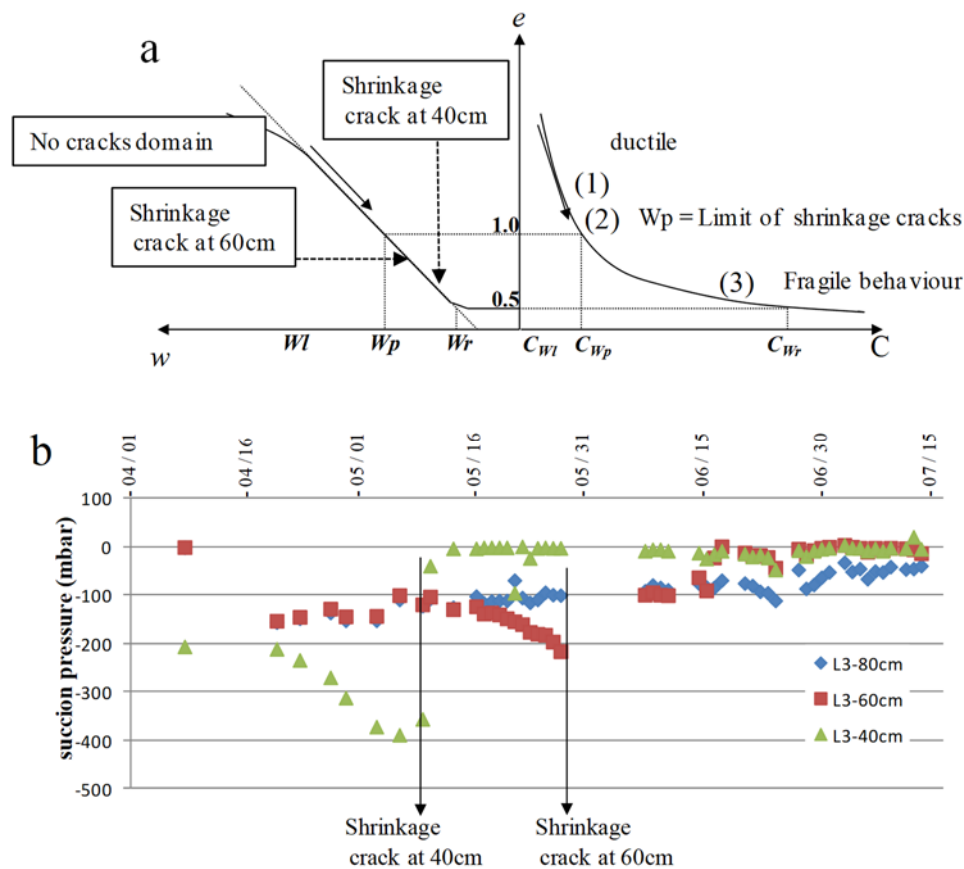


Figure 5. a) Schematic W-e-C microstructure evolution of the clay-matrix from the ductile to the fragile states with domains of shrinkage cracks. b) Associated tensiometric patterns recorded at depths of 40cm ($35 > W > 25$; solid state), 60 ($40\% > W > 35\%$ nearly limit of plasticity) and 80cm ($W > W_p$; plastic state) in a grassland of marsh in Rochefort.

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