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Modelling the behaviour of unsaturated non-active clays in saline environment

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ABSTRACT

The chemical composition of pore fluid and matric suction rule the mechanical behaviour of soils. In case of clays, their fabric changes in line with those variables. Since both the increase in matric suction and salinity cause a transition from an open to a close microstructure of low and medium activity clayey materials, a unique framework could tackle problems where salinity and saturation changes are expected.

This paper presents a simple elasto-plastic model capable of reproducing the behaviour of unsaturated clayey soils in saline environments. Changes in the pore fluid composition are addressed through the use of osmotic suction as a variable. The proposed model extends the Barcelona Basic Model for partially saturated soils to consider the effect of osmotic suction.

The model, implemented in the Thebes code, is calibrated for Boom Clay. The reproduced tests include mechanical loading at different matric and osmotic suctions in oedometric conditions, as well as more complex chemo-mechanical stress paths. Despite the simplicity of the formulation, the agreement between the experimental results and the simulations is encouraging. It seems that the modelling approach addresses the most important features of partially saturated soils with saline pore fluid which are slightly or moderately expansive.

1. Introduction

The chemo-hydro-mechanical response of clays is of significant importance in many geotechnical applications. A paradigmatic example is provided by sealing barriers for nuclear waste disposal. During their operational life, the clay barriers will likely be saturated by fluids having a chemical composition different from the compaction one (Castellanos et al., 2008; Musso et al., 2013). Furthermore, the heat generated by the canister may lead to water evaporation, inducing clay desaturation and a consequent increase of the concentration of the species dissolved in pore water. Swelling pressure development upon saturation, as well as shrinkage upon desiccation and upon salinization are anticipated; furthermore, changes of clay hydro-mechanical properties such as compressibility, permeability and shear strength may occur (Bolt, 1956; Mesri and Olson, 1971; Sridharan, 1991). The combined effect of degree of saturation changes and of the variation of the chemical composition of the pore water should thus be considered for a rational design, especially in presence of severe safety requirements. Pore fluid salinity and water content vary also in natural environments, such as in the Scandinavian ‘quick clays’. These are marine clays deposited in salt water and emerged in relatively recent geological times. Because of emersion, these formations are exposed to the circulation of freshwater. The following desalinization and increase in water content can lead to volumetric collapse and decrease of shear strength (Bjerrum, 1955; Torrance, 1974).

Unsaturated clays with salts dissolved in the pore fluid are thus subjected not only to matric suction, which is related to the interaction of pore fluid with the solid particles, but also to osmotic suction, which is related to the molar concentration of the dissolved salt in the pore fluid (Mitchell and Soga, 2005).

The understanding of microstructure evolution when the water content and the chemical concentration of salts change, is fundamental for an accurate replication of unsaturated clayey soil behaviour, as the microstructure changes directly affect macroscopic properties, such as

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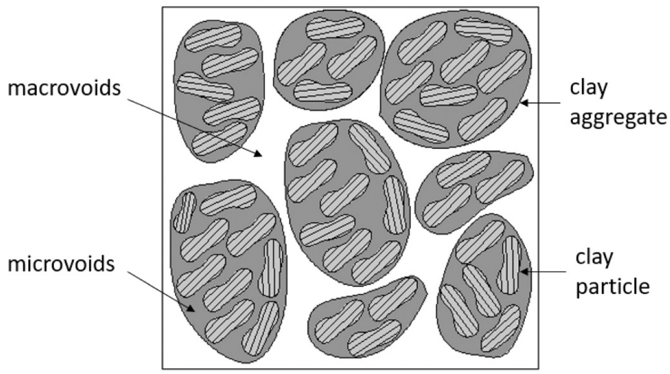

Fig. 1. Schematic representation of clay microstructure.

water retention curve, see e.g. Della Vecchia et al., 2019, Abed and Sołowski, 2021. As evidenced by ESEM (Environmental Scanning Electron Microscopy) and MIP (Mercury Intrusion Porosimetry) tests, compacted clay microstructure may consist of clay clusters or aggregates (see Fig. 1). After preparation, soil microfabric evolves with water content, as shown by, among others, Lloret et al. (2003) and Romero et al. (2011) for compacted clayey soils and Monroy et al. (2010) for reconstituted specimens. In particular, increasing matric suction has been proven to induce a reduction of aggregate size and a potential increase in macro-porosity. Many studies also investigated the effect of pore water salinity on the microstructure of saturated clays, e.g. Di Maio (1996) for reconstituted bentonite and Castellanos et al. (2006) and Musso et al. (2013, 2003) for compacted bentonites. Similarly, an increase in osmotic suction implies an increase in macro-porosity. In active clays, this can be triggered by the increase in the attractive forces between the faces of clay platelets in the aggregates, whereas for non-active clays a relevant role is played by electrical interactions between the faces and edges of clay particles (Horpibulsuk et al., 2011; Pedrotti and Tarantino, 2018; Van Olphen, 1977). Modelling approaches empirically accounting for microstructure changes have been proved to work well in predicting the response of active clays (Guimarães et al., 2013; Della Vecchia and Musso, 2016; Della Vecchia et al., 2019, among others), while less attention has been paid to the hydro-chemo-mechanical behaviour of non-active clays. Although in geo-environmental applications both matric and osmotic suction may change simultaneously, experiments on non-active clays have been mostly carried out considering separately either osmotic or matric suction changes. The coupled effect of matric and osmotic suction on an illitic clay (Boom clay) has been experimentally investigated, both microscopically and macroscopically, by Mokni et al. (2014).

Starting from the experimental evidence collected in Torrance (1974) and Musso et al. (2021) and briefly summarized in this paper, a constitutive framework capable of reproducing the mechanical effects of simultaneous matric and osmotic suction changes is proposed. The approach relies on the similarity between the phenomenological effects of matric and osmotic suction changes on material mechanical behaviour, which in turn depends on fabric evolution. To reproduce the macroscopic behaviour of the material due to partial saturation, the well-established Barcelona Basic Model (BBM) proposed by Alonso et al. (1990) has been exploited. Further constitutive models have been presented in the literature, including those proposed by Alonso et al. (2010), Blatz and Graham (2003), Cui et al. (1995), Della Vecchia et al. (2013), Gallipoli et al. (2003), Jommi (2000), Laloui and Nuth (2009), Mašín and Khalili (2008), Muraleetharan et al. (2009), Pereira et al. (2005) and Wheeler et al. (2003). The simplicity of BBM has been here preferred, due to the limited number of material parameters and the satisfactory predictive capabilities when the effect of partial saturation on slightly or moderately expansive clays is of concern. Since the late 90's several researchers presented elasto-plastic models for reproducing the chemo-mechanical behaviour of active clays (e.g. Gajo and Loret, 2003; Guimarães et al., 2013; Hueckel, 1997; Liu et al., 2005; Loret et al., 2002; Witteveen et al., 2013; Yan, 2018), while the macroscopic behaviour of non-active saturated clays subjected to changes in pore fluid salinity has been recently addressed in Musso et al. (2021, 2020) and Scelsi et al. (2021), by extending the Cam clay model to include the effect of saline pore water.

This work aims at providing a simple model to reproduce the chemo-mechanical behaviour of non-active unsaturated clays by joining the proposals of BBM and of Musso et al. (2020, 2021). The model, implemented in the Thebes code (Abed and Sołowski, 2017, 2020), is used to simulate experiments on compacted Boom clay subject to different stress paths at varying matric and osmotic suctions. The procedure depicted is sufficiently general and can be applied to most constitutive models developed in the framework of elasto-plasticity with generalized hardening.

2. The role of fabric in the modelling framework

Matric suction is related to capillary forces, acting on solid particles in granular materials and on clusters/aggregates of clay particles. Both

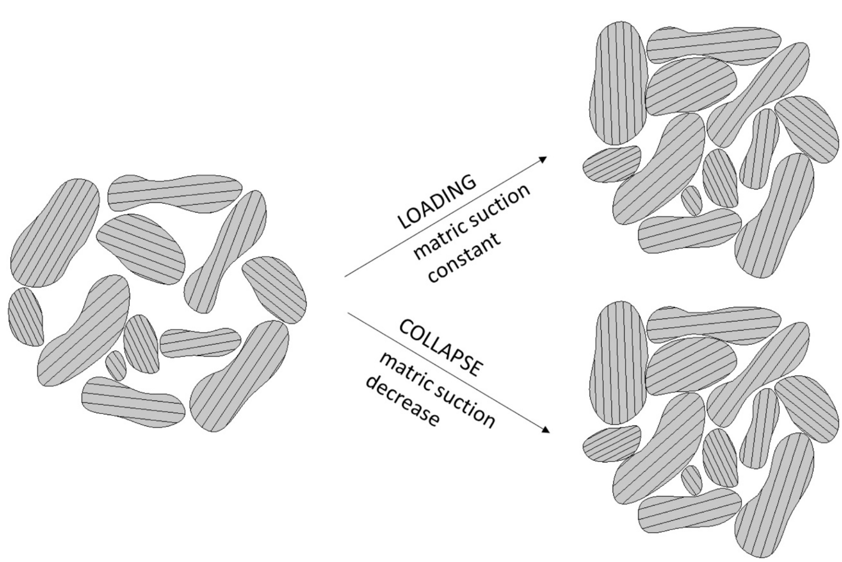

Fig. 2. Microstructure evolution of a partially saturated soil with open fabric subjected to mechanical loading or to wetting.

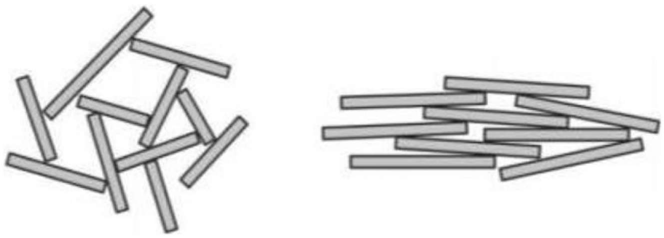

Fig. 3. (left) Flocculated fabric resulting from deposition in saline environment and (right) aggregated fabric formed in freshwater.

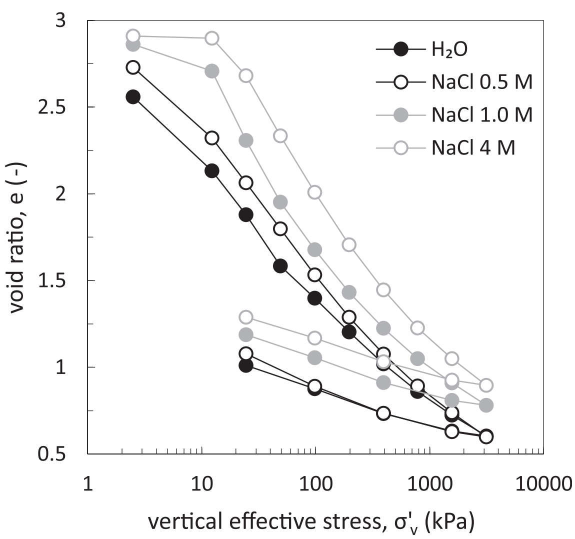

Fig. 4. Oedometer compression of illite saturated with NaCl solutions of different molarity (re-elaborated from Musso et al., 2021).

soil deposition and compaction may induce an 'open fabric' (Alonso et al., 1990), that generally refers to the existence of macro-voids, i.e. voids between the clusters/aggregates of particles, as depicted in Fig. 1. If an unsaturated material is subjected to mechanical loading at constant suction, plastic strains may develop. However, from the constitutive modelling point of view, the higher the matric suction, the larger the size of the elastic domain, and as a consequence the position of the Normal Compression Line (NCL) in the compression plane moves to higher void ratio as the matric suction increases. As a consequence, if an unsaturated material with an open fabric is subjected to wetting at constant stress, a reduction in matric suction (i.e. a reduction in capillary forces) makes the current void ratio non-compatible with the applied stress and thus compressive plastic strains develop (the so-called wetting induced collapse). Fig. 2 provides the schematic of these two irreversible processes in a material with an open microstructure. From the constitutive point of view, the possibility of having plastic strains related to both mechanical loading and suction decrease has been modelled by the so-called Loading-Collapse (LC) curve, as proposed by Alonso et al. (1990) in the BBM model and then recognised as a fundamental feature in any constitutive model for unsaturated soils.

It is acknowledged that also pore water salinity influences the fabric of non-active clays. The extent of this influence depends on the soil formation process and on the electro-chemical environment. When deposition of non-active clays occurs in salty water, the material tends to have an (open) flocculated fabric, whereas a face to face aggregated fabric is formed in freshwater (see Fig. 3) (see, e.g. Horpibulsuk et al., 2011, and Pedrotti and Tarantino, 2018). This has been proven to work also for compacted clays. The different fabrics imparted are responsible for different engineering behaviours, like collapse and expansion (Collins and McGown, 1974).

Recently, Musso et al. (2020, 2021) proposed a link between the fabric of non-active clayey materials and their phenomenological behaviour upon chemo-mechanical solicitation, evidencing the role of the open fabric imparted upon deposition on the following compression behaviour. A larger osmotic suction conveys the material a more open fabric. Consistently, also with osmotic suction the position of the NCL moves to higher void ratios and its slope changes. Fig. 4 provides the experimental results for illite specimens, prepared by mixing dry illite powder with an amount of liquid in order to impose an initial void ratio $e \cong 1.2e_L$ (where e_L is the void ratio at liquid limit).

When an open fabric is created due to the presence of salt and then salt is removed (i.e. osmotic suction decreases), compressive irreversible strains are anticipated, in the same way as wetting induces collapse for unsaturated soils. In fact, experimental evidences (see e.g. Torrance, 1974) prove that a reduction in osmotic suction (desalinization) at a given confining stress may cause irrecoverable volumetric compression, i.e. desalinization induced collapse, especially if the material initially lies on the NCL corresponding to the relevant osmotic suction. Vice versa, if the material is strongly over-consolidated (i.e. the fabric is closed), desalinization induces swelling. This is in accordance with the increase of repulsive forces between particles caused by the increase in thickness of the double layer, which is an elastic process.

The analogy with matric suction works also for mechanical loading at constant osmotic suction, as also its increase induces an increase of the elastic domain. In fact, a preconsolidation stress higher than the initial one is found when the osmotic suction of a normally consolidated sample is increased and compression is then imposed. On the other hand, the preconsolidation stress of a normally consolidated sample whose osmotic suction has been decreased is equal to the initial one (these evidences are available in the experimental works by Torrance, 1974 and Barbour and Yang, 1993, among others).

Given the analogous phenomenological effects of osmotic and matric suction changes, later in the paper we assume that the combination of chemical and hydraulic effects can be reproduced with the same approach, i.e. considering the evolution of the NCL of the material due to both the effects. Remarkably, particle/cluster deformation is very small for non-active clays, both if induced by hydraulic and chemical effects, and their role is considered negligible in promoting irreversible deformations.

3. Modelling framework

The macroscopic behaviour of partially saturated soils can be described by the widely known Barcelona Basic Model and its successive modifications (Alonso et al., 1990), whereas the chemo-mechanical model presented by Musso et al. (2020, 2021) can define the macroscopic behaviour of soils saturated with the saline pore fluid. The two models are briefly presented in the following.

3.1. Barcelona Basic Model (BBM)

The classical BBM, developed in the framework of hardening elastoplasticity, uses net stress $\sigma'' = \sigma - u_a$ and matric suction $s = u_w - u_a$ as independent variables, where σ, u_w and u_a are the total stress, pore water pressure and pore air pressure, respectively.

In the model, the elastic changes of specific volume v are related to the variations of p'' and s as follows:

$$dv^e = -\kappa \frac{dp''}{p''} - \kappa_s \frac{ds}{s + p_{atm}} \quad (1)$$

where κ is the slope of the elastic swelling line, κ_s is the compressibility coefficient for matric suction changes and p_{atm} is the atmospheric pressure.

As the water content influences the soil fabric, BBM defines the Normal Compression Lines (NCL) for different values of suction in the v

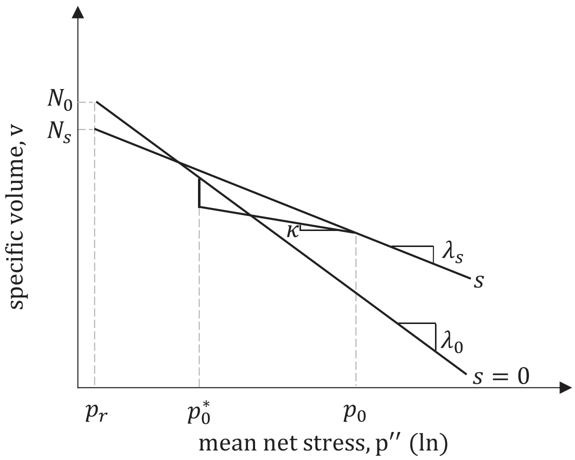

Fig. 5. Compression curves for soil saturated with distilled water (s = 0) and for a partially saturated soil. Relationship between preconsolidation stresses p_0^* and p_0.

$-\ln p''$ plane as:

$$v = N_s - \lambda_s ln\frac{p''}{p_r} \tag{2}$$

where N_s is the specific volume for a reference mean stress p_r and λ_s is the slope of the normal compression line. Both N_s and λ_s are functions of suction (see Fig. 5).

BBM assumes the loading-collapse (LC) yield curve in the $s - p''$ plane as:

$$p_0 = p_r\left(\frac{p_0^*}{p_r}\right)^{\frac{\lambda_0 - k}{\lambda_s - \kappa}} \tag{3}$$

where p_0 is the preconsolidation pressure at suction s, p_0^* is the preconsolidation pressure at zero matric suction and λ_0 is the slope of the normal compression line in saturated conditions. Eq. (3) introduces a dependence of the size of the yield surface on suction. Its shape in the $p'' - s$ plane expands when the suction increases and contracts when the suction decreases. When the stress path crosses the LC curve, the development of the plastic strains may be due to a reduction of suction or to an increase of load. This agrees with the consideration on the action of matric suction on soil particles explained in Section 2.

3.2. Chemo-mechanical model

Musso et al. (2020, 2021) proposed a model for saturated low to medium activity clays, developed based on the phenomenological and experimental evidences regarding the role of fabric in saturated conditions as induced by different osmotic suctions.

Formulated in the framework of elasto-plasticity with generalized hardening (Tamagnini and Ciantia, 2016), the chemo-mechanical model has been successfully used to reproduce the effects of changes in the applied osmotic suction and stress (Scelsi et al., 2021). The model uses the Terzaghi effective stress, σ' and the osmotic suction, π, as environmental variable. This has been set to depend on the chemical activity of the components in solution and, at low concentrations, can be described by the van't Hoff equation (Nelson and Cox, 2004):

$$\pi = icRT \tag{4}$$

where i is the number of dissolved species (e.g. 2 for NaCl and 3 for $CaCl_2$), c is the molar concentration of the electrolyte (mol/m^3), R is the universal gas constant (8.3144 J mol^{-1} K^{-1}) and T is the absolute temperature (K).

In this model, the elastic changes of specific volume are related to variations of p' and π as follows:

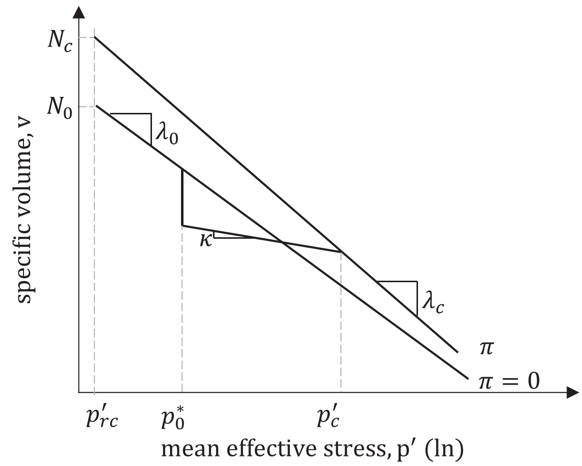

Fig. 6. Compression curves for soil saturated with distilled water (π = 0) and for soil saturated with a saline solution. Relationship between preconsolidation stresses p_0^* and p_c'.

$$dv^e = -\kappa\frac{dp'}{p'} - \kappa_\pi\frac{d\pi}{\pi + \pi_{ref}} \tag{5}$$

where κ_π is the elastic compressibility for changes in osmotic suction and π_{ref} is the reference osmotic suction.

As the pore fluid chemistry influences the soil fabric, the normal compression line in the semilogarithmic plane $v - p'$ depends on the saline concentration:

$$v = N_c - \lambda_c ln\frac{p'}{p'_{rc}} \tag{6}$$

where the intercept N_c and slope of the Normal Compression Line λ_c are both functions of the osmotic suction, while p'_{rc} is a reference pressure (see Fig. 6).

The expression of the yield curve in the $\pi - p'$ plane reads:

$$p'_c = p_0^*\left(\frac{p_0^*}{p'_{rc}}\right)^{\frac{\lambda_0 - \lambda_c}{\lambda_c - \kappa}} exp\left(\frac{N_c - N_0}{\lambda_c - \kappa}\right)\left(\frac{\pi + \pi_{ref}}{\pi_{ref}}\right)^{\frac{\kappa_\pi}{\lambda_c - \kappa}} \tag{7}$$

where p'_c is the preconsolidation pressure corresponding to osmotic suction π, N_0 and N_c are the intercepts at the reference pressure p'_{rc} of the Normal Compression Lines of the material saturated with distilled water and with a saline solution, respectively. Fig. 6 provides a schematic representation of the compression curves at varying osmotic suctions; it also shows the relationship between the preconsolidation pressures p_0^* and p'_c. Eq. (7) identifies a dependence of the chemical preconsolidation pressure p'_c on pore fluid salinity and, similarly to the BBM, when the stress path crosses the yield surface, plastic strains may develop due to a reduction of the osmotic suction or due to an increase of the stress. Analytical details on the derivation of this expression can be found in Musso et al. (2020, 2021).

Since the dependence of the volumetric virgin compressibility λ on the pore fluid salinity for non-active clays is quite limited, λ_c can be assumed to be constant and coincident with λ_0. Assuming also that $N_0 = N_c$, Eq. (7) simplifies to:

$$p'_c = p_0^*\left(\frac{\pi + \pi_{ref}}{\pi_{ref}}\right)^{\frac{\kappa_\pi}{\lambda_0 - \kappa}} \tag{8}$$

The yield curve in the $(p' - \pi)$ plane is represented in Fig. 7a and shows a similar trend to the BBM LC curve (Fig. 7b).

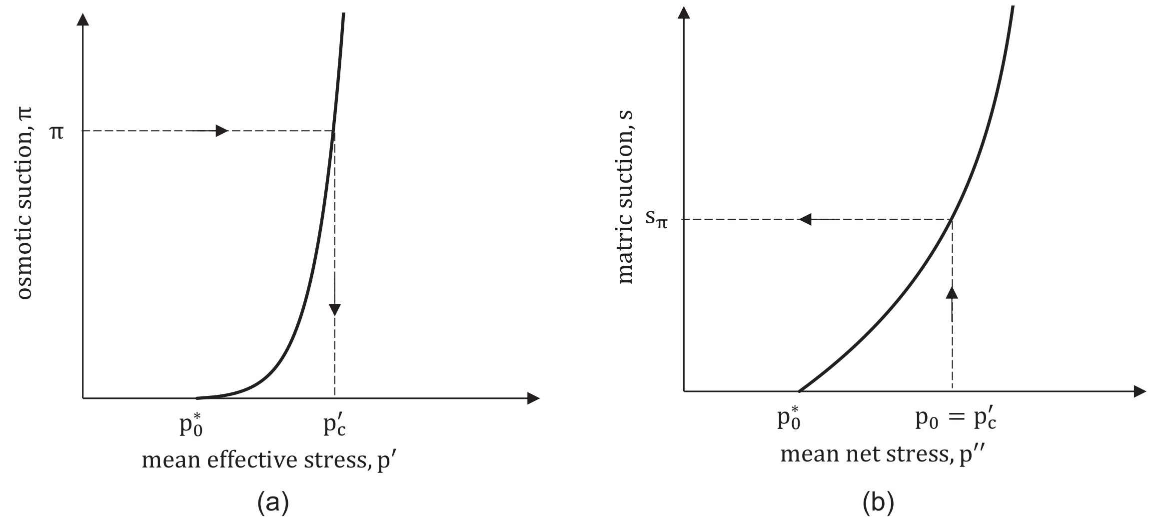

Fig. 7. Procedure to estimate the matric suction equivalent to the osmotic suction using the loading collapse curve introduced (a) in the chemo-mechanical model presented by Musso et al. (2020, 2021) in the p'- π stress space and (b) in the BBM in the p''-s stress space.

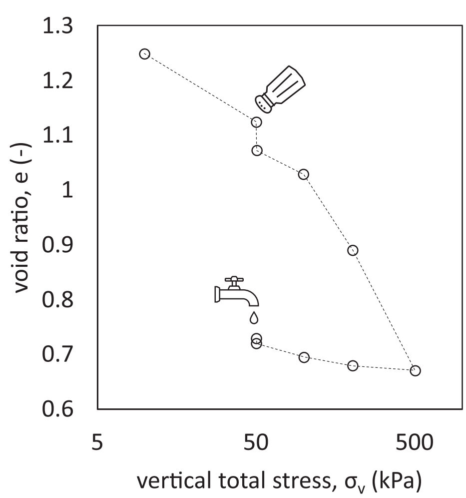

Fig. 8. Experimental results (from Mokni et al., 2014) of a chemo-mechanical loading path in oedometric conditions in the compression plane.

3.3. *Combination of partial saturation with salinity*

The above described models are founded on separate evidences concerning the behaviour of non-active materials independently exposed either to matric suction or to osmotic suction changes. The roles of the two suctions on the one-dimensional compression of non-active clays have been proved to be very similar and thus, from the modelling point of view, they could be simulated with similar constitutive tools. A macroscopic way to quantify the combination of the effects is through the Loading Collapse curve. For partially saturated soils the Barcelona Basic Model links the preconsolidation pressure for materials fully saturated with pure water, p_0^* to the yield mean net stress for partially saturated materials, p_0, through Eq. (3). Following the approach proposed by Alonso et al. (1990) for the unsaturated soils, the chemo-mechanical model introduces a relation between the preconsolidation pressure for the material saturated with distilled water, p_0^* and the yield mean effective stress for material saturated with saline solutions with osmotic suction π, $p_c^{'}(\pi)$ through Eq. (7). Both yield curves in the $p'' - s$ plane and in the $p' - \pi$ plane play the role of the Loading Collapse (LC) curve and have a similar trend (see Fig. 7).

A possible approach to combine the effect due to the partial saturation with that caused by the salinity in the soils is to add them in terms of Loading Collapse curve. Since the yield curve in the $p'' - s$ plane of the BBM and the yield curve in the $p' - \pi$ plane of the chemo-mechanical model are used to reproduce the macroscopically similar behaviour, we can assume that, for modelling the joint effects of the pore fluid salinity and the partial saturation within a unique framework, the osmotic suction can be introduced in the BBM model as an equivalent matric suction. Introducing in the BBM changes in the matric suction equivalent to the osmotic suction would then cause similar effects as those caused by the osmotic suction changes in the Musso et al. (2020, 2021) model. Details on the procedure will be presented in Section 4.

As evidenced in unsaturated soils, a matric suction increase beyond the maximum past suction experienced in the soil history may induce irrecoverable strains. In the original BBM formulation this aspect is considered by introducing the Suction Increase (SI) yield curve, whereas this aspect was not introduced in the Musso et al. (2020, 2021) model because of the scarcity of experimental data concerning salinization / desalinization cycles under constant stress in non-active clays. However, Mokni et al. (2014) performed chemo-mechanical tests in oedometer conditions on compacted Boom clay. Fig. 8 shows the experimental results on a specimen, prepared with distilled water, that, after an initial mechanical loading, was exposed to a sodium nitrate solution. The specimen was then subjected to a mechanical loading/unloading path and finally exposed to the distilled water. According to Musso et al. (2021) and because of the shape of the LC as provided in Fig. 7a, both the salinization and the desalinization in Fig. 8 would cause only elastic strains, and the changes in void ratio as predicted through Eq. (5) would be the same. This is different from the experimental evidence, as the reduction of void ratio due to salinization is larger than the increase in void ratio due to desalinization. Therefore, it is here assumed that a 'virgin' increase of osmotic suction induces plastic volumetric strains. According to the BBM, this is achieved through the introduction of a SI yield locus also for salinization, thus allowing to reproduce this experimental evidence.

The evidences and concepts here introduced were used to develop a simple model for unsaturated soils with saline pore fluid. The model assumes that the effects on clay fabric caused by matric suction and by pore fluid salinity changes can be handled in similar ways and then merges two validated approaches for slightly or moderately expansive clays.

4. Formulation of the model

In order to account for the joint effects of the partial saturation of the soils and of the salinity of the pore fluid, the Barcelona Basic Model is enhanced to consider the effect of osmotic suction.

4.1. Dependence of soil compressibility on matric suction

The distribution of pores between clay particles (i.e. material fabric) influences the phenomenological stress-strain response of the material (Della Vecchia et al., 2013). For example, the experimental evidence suggests that the slope of the virgin compression line may depend on matric suction. Alonso et al. (1990) proposed a monotonic decrease of $\lambda(s)$ when s increases. However, the dependence of $\lambda(s)$ on suction is material specific and other experimental data showed that the slope of the NCL increases with the increasing suction (see e.g. Della Vecchia, 2009; Koliji, 2008; Romero, 1999; Wheeler and Sivakumar, 1995). With reference to the aggregated soils, Koliji (2008) interpreted the increase in the post-yield compressibility at increasing suction as a plastic degradation mechanism. Increasing the applied effective stress, the soil destructurates, and the compression index increases. Della Vecchia et al. (2013) investigated Boom clay, a moderately swelling kaolinitic-illitic clay, and found that the slope of the normal consolidation line increased with increasing suction. They interpreted the dependence of the volumetric compressibility on water content to be the consequence of the related change of the size of the aggregates. At increasing matric suction, the aggregates shrink, leading to a higher amount of macrovoids and to higher compressibilities.

In order to replicate the phenomenon of the increase in the soil compressibility with the increase of the matric suction for some materials, the expression of the evolution of the soil stiffness with suction introduced in the classical Barcelona Basic Model has been modified to increase model flexibility. This modification is introduced in the next section, where the formulation of the new model is given.

4.2. Extension of the BBM to saline soils

The models described in Section 3 can be combined in order to reproduce the volumetric behaviour of unsaturated clays of moderate activity with saline pore fluid.

Both models are formulated within the theory of hardening plasticity and extend the modified Cam Clay to the partially saturated conditions (BBM) and to the soils saturated with saline solutions (chemo-mechanical model). Their yield functions were derived from the observed volumetric behaviour, introducing a dependence on the normal compression line on the static variables, i.e. s for the BBM and π for the chemo-mechanical model. Furthermore, both yield curves play an analogous role in the development of plastic strains.

Since, as explained in Section 2, the effect of the salinity on the clay microstructure is similar to the effect of partial saturation, a matric suction equivalent to the osmotic suction, s_π can be introduced in the BBM, so that both matric and osmotic suctions can be accounted for in a single framework.

According to the chemo-mechanical model, when a saline solution is present in a soil, the preconsolidation pressure increases from p_0^* to p_c' (Fig. 7a). The equivalent matric suction s_π is the matric suction that would be obtained from the LC curve of the BBM passing from the saturated preconsolidation pressure, p_0^* to p_c' (see Fig. 7b). Therefore, imposing that $p_0 = p_c'$, the expression of $\lambda_s(s_\pi)$ can be obtained from Eq. (3):

$$\lambda_s = (\lambda_0 - \kappa)\frac{ln\frac{p_0^*}{p_r}}{ln\frac{p_c'}{p_r}} + \kappa \tag{9}$$

The Barcelona Basic Model expression describing the variation in soil compressibility with matric suction is given by:

$$\lambda_{s,BBM} = \lambda_0\left[(1-r)exp(-\beta s_\pi) + r\right] \tag{10}$$

with r being the model parameter related to the maximum compressibility of the soil and β the parameter which controls the rate of increase of soil compressibility with suction.

Since the experimental evidence given in Section 4.1 show that the soil compressibility of some clayey material, e.g. Boom Clay, increases with matric suction, the expression describing the variation in soil compressibility with suction λ_s is assumed to have a trend similar to that in the classical BBM expression of λ_s mirrored with respect to λ_0

$$\lambda_s = -\lambda_{s,BBM} + 2\lambda_0 \tag{11}$$

Substituting (10) in (11), we obtain the expression of the matric suction equivalent to the osmotic suction, s_π

$$s_\pi = -\frac{1}{\beta}ln\left[\frac{\lambda_s + \lambda_0(r-2)}{\lambda_0(r-1)}\right] \tag{12}$$

An appropriate combination of parameters (κ, λ_0, p_r, r) should be chosen so that the arguments of the logarithmic functions in Eqs. (9) and (12) would be positive for every value of p_0^*. Apart from $\lambda_0 > 0$, an appropriate choice of r is necessary. When the ratio $(2\lambda_0 - \lambda_s)/\lambda_0$ is smaller than 1, the parameter r has to be smaller than $(2\lambda_0 - \lambda_s)/\lambda_0$ or greater than 1; instead when the ratio $(2\lambda_0 - \lambda_s)/\lambda_0$ is greater than 1, the parameter r has to be smaller than 1 or greater than $(2\lambda_0 - \lambda_s)/\lambda_0$.

When the saline pore fluid is present in an unsaturated soil of given matric suction s, the effect of partial saturation and of chemistry are taken as equivalent in terms of void ratio. As discussed in Section 2, the equivalence of the microstructural effects of the matric and osmotic suctions leads to a common Loading Collapse curve for both effects. The BBM is enhanced by introducing an equivalent suction s_ψ, used in the same way as suction in the original BBM:

$$s_\psi = s + s_\pi \tag{13}$$

As introduced in Section 3, a suitable constitutive model for unsaturated saline soils should have a yield surface for the first ever chemical loading. The first increase in salt content causes a change in the soil structure, leading to plastic volumetric deformations. Therefore, we introduce a yield function conceptually similar to the suction increase yield locus of the BBM:

$$\pi = \pi_0 \tag{14}$$

The maximum osmotic suction ever experienced by the soil π_0 should also be converted in an equivalent matric suction $s_{\pi,\,0}$ in order to be introduced in the BBM model.

Once this yield locus is reached, the following plastic volumetric strain will be induced:

$$d\varepsilon_{vs}^{p} = -\frac{\lambda_\pi}{v}\frac{ds_{\pi,0}}{(s_{\pi,0} + p_{atm})} \tag{15}$$

Where λ_π is the stiffness parameter for changes in (osmotic) suction for virgin states of the soil. This enhanced model has been implemented in Thebes Finite Element code (Abed and Sołowski, 2017, 2020).

5. Model predictions and comparison with experimental data

The model presented in Section 4 is validated against experimental results of osmotic and matric suction controlled oedometer tests performed on Boom Clay (Mokni et al., 2014).

5.1. Material and experimental procedure

This material has been extensively studied in the last decades (e.g. Della Vecchia, 2009; Romero, 1999; Smith et al., 2009) as a possible host material for the disposal of radioactive waste in Belgium. The dominant

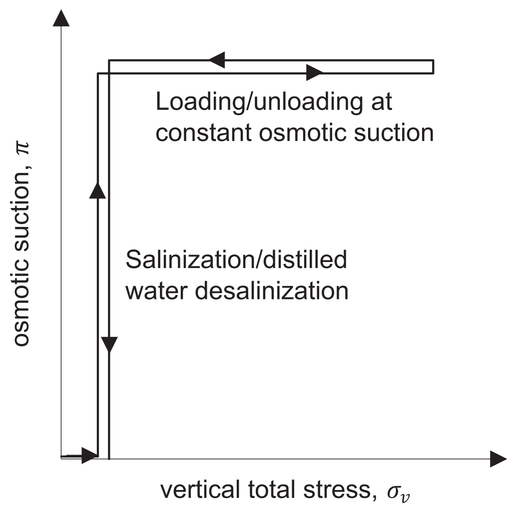

Fig. 9. Chemo-mechanical stress path of the "exposed" specimens.

composition of the clay fraction, which represents 65% to 70% of the weight of the total solids, is 20–30% kaolinite, 20–30% illite and 10–20% interstratified smectite. The non-clayey fraction is dominated by quartz (15–25%) and calcite (< 5%). Its liquid limit is 86% and the plastic limit 29–40%; other relevant material properties can be found in Romero (1999).

Mokni et al. (2014) performed an extensive laboratory programme on compacted specimens to investigate the osmotic and matric suction influence on the hydro-mechanical response of Boom Clay. Two series of specimens have been tested using Boom Clay powder targeting an initial void ratio around e = 1.25. The "mixed" specimens have been obtained by mixing dried Boom Clay powder with saline solutions (4 M, 5.4 M of $NaNO_3$). The "exposed" specimens have been remoulded using distilled water and afterwards exposed to various saline solutions. The applied stress paths in the $\sigma_v - \pi$ plane are sketched in Fig. 9. Once statically compacted, the specimens were subjected to mechanical stress paths in oedometric conditions at full saturation (s = 0 kPa) and at 500 kPa matric suction. Fig. 10a and b show the experimental points in the compression plane of the mixed specimens having 0, 11,000 kPa, 20,000 kPa osmotic suction at, respectively, $s = 0$ kPa and $s = 500$ kPa. Fig. 11a, b and Fig. 12 show the experimental points in the compression plane for the specimens exposed to $NaNO_3$ salinization ($\pi = 31000$ kPa in Fig. 11a,b, $\pi = 2000$ kPa in Fig. 12) under constant effective stress. The tests were performed both at full saturation $s = 0$ kPa (Fig. 11a and Fig. 12) and at a matric suction $s = 500$ kPa (Fig. 11b). After reaching chemical equilibrium, the specimens were subjected to a loading/unloading path and finally exposed to distilled water.

5.2. Material properties and model parameters

The proposed model was used to simulate the oedometer tests performed by Mokni et al. (2014). A yield stress of 90 kPa was identified for the saturated conditions. The parameters for Boom Clay are listed in Table 1. The values of κ and λ_0 were calibrated on the compression response of the material saturated with distilled water. The slope of the critical state line M was computed from the friction angle $\phi' = 22^o$, obtained from shear tests by Mokni et al. (2014). The chemical compressibility κ_π was calibrated on the mixed specimens prepared at osmotic suctions different from zero (4 M, 5.4 M $NaNO_3$), whereas parameters related to partial saturation (r, β, p_{ref}^{BBM}) were obtained from the mixed specimen having matric suction equal to 500 kPa.

5.3. Discussion on model predictions

The predictions of the model, shown in Fig. 10a and b for the mixed specimens, are in good agreement with the experimental results. In accordance with the shape of the loading collapse curve, the model predicts an increase of the preconsolidation pressure at increasing osmotic and matric suction. The influence of osmotic suction on the yielding stress reduces at increasing matric suction: in Fig. 10a the mixed specimens prepared with saline solution show a clear increase in the preconsolidation stress, whereas in Fig. 10b the effect of osmotic suction is almost negligible. On the other hand, the osmotic suction slightly influences the soil compressibility ($\lambda_0 = 0.28$ for $\pi = 0$ kPa, $\lambda_0 = 0.3$ for $\pi = 20{,}000$ kPa at full saturation, $\lambda_s = 0.38$ at matric suction equal to 500 kPa for $\pi = 0$, 11,000, 20,000 kPa).

The model was also successfully used to simulate the oedometer tests on the specimens exposed to changes in pore water salinity. In all the tests the elastic swelling caused by the re-exposure to distilled water is barely visible. Therefore, the introduction of the SI is a necessary requirement for this model in order to reproduce the large strains that arise after first exposure to the sodium nitrate solution. The stiffness parameter λ_π was calibrated on the salinization path for the saturated specimen (Fig. 11a). Fig. 11 and Fig. 12 show the results of the

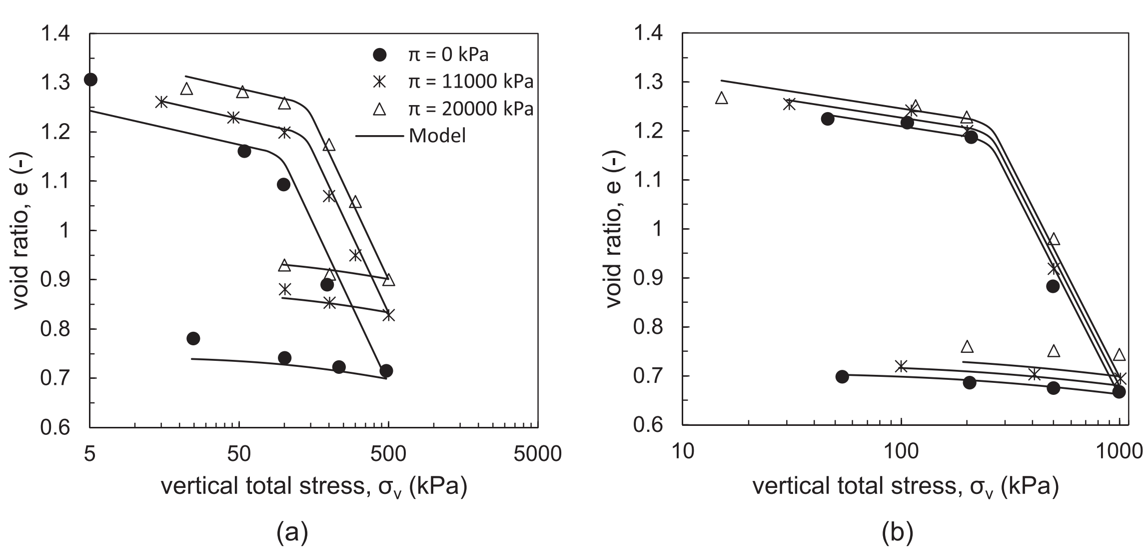

Fig. 10. Experimental results of Boom Clay subjected to mechanical loading path at different osmotic suctions (after Mokni et al., 2014) and model predictions (a) at full saturation, s = 0 kPa (b) at a matric suction s = 500 kPa.

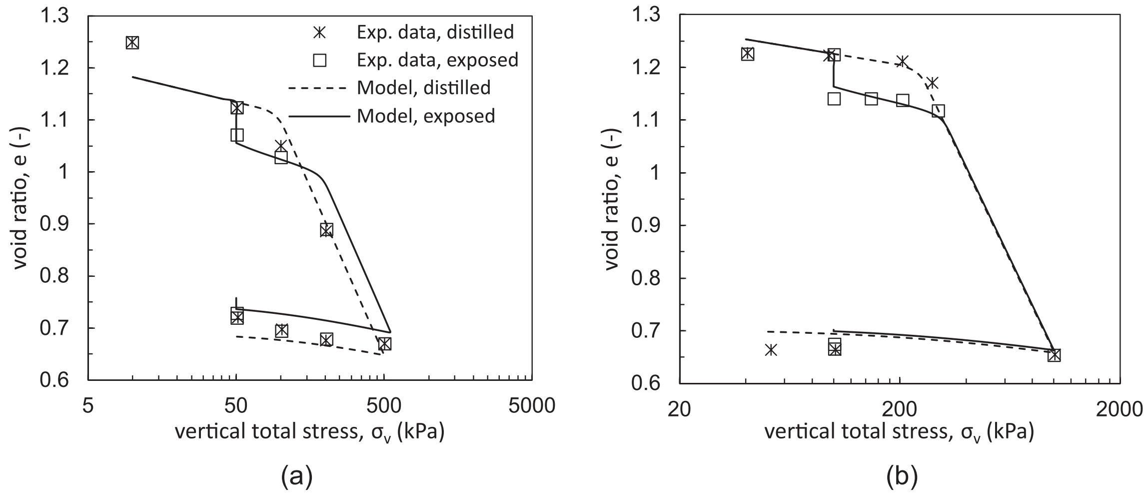

Fig. 11. Experimental results of Boom Clay subjected to chemo-mechanical loading path (after Mokni et al., 2014) and model predictions (a) at full saturation, s = 0 kPa (b) at a matric suction s = 500 kPa.

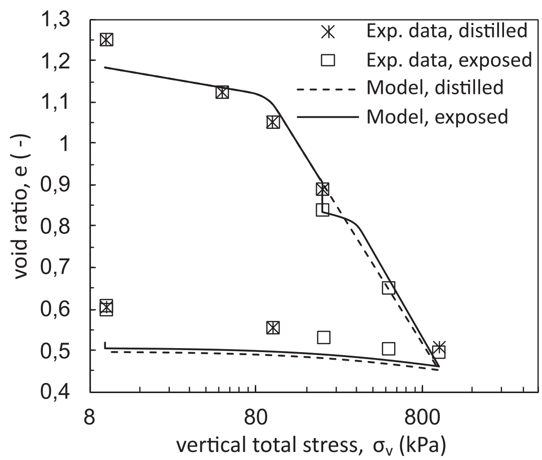

Fig. 12. Experimental results of Boom Clay subjected to chemo-mechanical loading path (after Mokni et al., 2014) and model predictions at full saturation, s = 0 kPa.

simulation in the compression plane for Boom clay at the full saturation and at the partial saturation.

In accordance with the convex shape of the yield function in the $p'' - s$ plane, the model predicts a NCL for the exposed specimen shifted with respect to the NCL of the distilled material. The shifting of the saline NCL line becomes negligible when the material is partially saturated (Fig. 11b). Once again this is due to the small value of s_π (52 kPa, corresponding to $\pi = 31{,}000$ kPa) with respect to s_m (500 kPa).

All the model predictions shown in Figs. 10, 11, 12 display a smooth transition from elastic to elasto-plastic response. This transition is due to the development of deviatoric strains at the inception of plasticity when the oedometer conditions are imposed. As it can be seen in Fig. 13, the stress path in p-q plane experiences a transition from an obliquity tending to the earth pressure coefficient at rest in overconsolidated conditions to an obliquity tending to the earth pressure coefficient for normally consolidated material.

6. Conclusions

Microstructural observations show that both the increase in matric suction and in pore fluid salinity cause a transition from an open to a close fabric of low and medium activity clayey materials.

These similar effects allow the introduction of a unique framework for soils partially saturated with saline solutions, where salinity and saturation changes are expected.

The paper proposes a simple elasto-plastic model, extending the Barcelona Basic Model to cover unsaturated clayey soils in saline environment. The model formulation aims to reproduce the macroscopic effects of fabric changes in the clay induced by the hydro-chemical phenomena. The model introduces the effect of the osmotic suction in the BBM as an equivalent matric suction. Based on the analysis of the microstructural changes of clay materials, the model assumes that the equivalent matric suction in the BBM causes the same effects on void ratio as those caused by the osmotic suction in the chemo-mechanical model. Starting from the latter model proposed by Musso et al. (2021, 2020), the equivalent matric suction stems from the expression of the hardening parameter p_c'. The modelling of the partially saturated soils with saline pore fluid adds up the equivalent matric suction to the matric

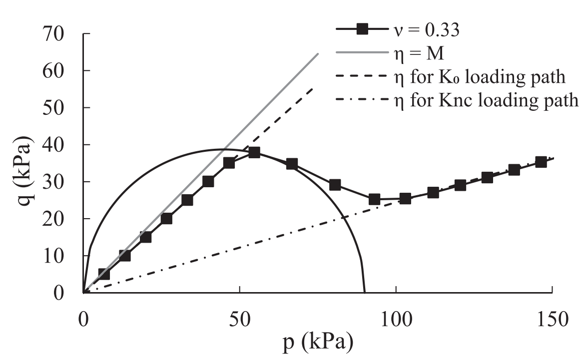

Fig. 13. Transition from the stress path η tending to K_0 to the obliquity η tending to K_{nc} when the soil yields in the q-p plane.

Table 1
Model parameters and initial value of $s_{\pi,0}$ and p_0^* used in the simulations of the chemo-mechanical loading paths in oedometer conditions on Boom Clay.

κ (−)	λ_0 (−)	ν (−)	M (−)	p_{rc}' (kPa)	κ_π (−)	r (−)	β (kPa^{-1})	k_s (−)	p_r (kPa)	λ_π (−)	$s_{\pi,0}$ (kPa)	p_0^* (kPa)
0.03	0.28	0.33	0.86	1	0.01	0.65	0.008	0.05	3000	0.26	1	90

suction characterising the unsaturated soils.

The formulation reproduces the stiffness changes of the soil induced by the suction variations and accounts for the plastic chemical deformations that develop when the clayey material is exposed for the first time to an increase in osmotic suction.

The model, implemented in the code Thebes, was calibrated based on the oedometer tests on Boom Clay performed at different matric and osmotic suctions; it was proved to be effective in predicting the complex chemo-mechanical stress paths at varying matric suctions.

The theoretical formulation, despite its simplicity, can be used to reproduce the joint effects of the partial saturation and the salinity on moderate plasticity clays. Yet an extension of the proposed model is likely necessary to approximate the behaviour of highly expansive clays.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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