IV International Conference on Computational Methods for Coupled Problems in Science and Engineering
COUPLED PROBLEMS 2011
M. Papadrakakis, E. Oñate and B. Schrefler (Eds)

A COUPLED MODEL OF MECHANICAL BEHAVIOUR AND WATER RETENTION FOR UNSATURATED SOILS WITH DOUBLE POROSITY

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Key words: Unsaturated soil, constitutive modeling, hydro-mechanical coupling, soil structure; double porosity, plasticity.

Abstract. Many natural soils and engineering geomaterials, such as aggregated soils and compacted clay pallets, exhibit two levels of porosity corresponding to the inter- and intra-aggregate pores within their hierarchical structure. Mechanical behavior of these materials, in particular when unsaturated, is an issue of added complexity which should be described an appropriate constitutive framework. A coupled water retention–mechanical constitutive model for unsaturated soils with double porosity is presented here. Based on the multi-scale experimental results, the model incorporates the inter-particle bonding, fabric and partial saturation effects in a single framework. It is formulated within the framework of hardening elasto-plasticity and is based on the critical state concept. The mechanical model is coupled with the water retention law which itself takes into account the two levels of porosity. The coupling is made through the expression of the effective stress and the evolution of the preconsolidation pressure with suction. On the other hand, the mechanical model at the macro-scale is also coupled with the pore-scale behavior of the materials through an internal variable which accounts for the evolution of the soil structure. The model is used for numerical simulation of the behavior of aggregated and bonded soils. Comparison of numerical simulations and the experimental results show that the model can successfully address the main features in the behavior of unsaturated soils with double porosity.

1 INTRODUCTION

Constitutive modeling of unsaturated soils is a subject of increasing interest owing to its importance in a large number of geotechnical engineering problems. Although the early developments were focusing on a homogeneous continuum concept and a single porosity, further evaluation of structured porous media, such as aggregated soils, fissured clays and fractured rocks, revealed the necessity of considering a structure with inter-particle bonding and at least two distinct values of porosity linked to macro- and micropores. Hence, the concept of double porosity [1,2] usually applies for these materials.

Improvements of constitutive models for natural bonded soils have been proposed by introducing a dependency of the size of the yield limit on the inter-particle bonding [3-9].

These models often ignore the soil fabric effects and use ad hoc relations to describe the soil structure evolution. Moreover, these models are mainly developed for saturated soils and only few works have looked into the coupled effects of soil structure and partial saturation [10, 11].

When unsaturated, the pores are infiltrated by more than one fluid. Hence, beside the improvement of the mechanical constitutive model for capillary effects, an additional constitutive relation is required to describe the liquid retention of the pores. Such a relation becomes of particular importance when the constitutive stress includes a combined function of suction and degree of saturation, as in the models of Bolzon et al. [12] and Wheeler et al. [13]. It is, therefore, important to introduce a coupling between the mechanical and the water retention constitutive relations.

In the present paper, a mechanical constitutive model coupled with the water retention relation is proposed for unsaturated soils with double porosity. It incorporates the inter-particle bonding, fabric and partial saturation effects in a single framework. Also, it allows a two-way coupling between water retention and mechanical behavior. The model development is based on the multi-scale experimental results of unsaturated aggregated soils presented in [14, 15] and that is briefly reviewed in the next section. The two parts of the model corresponding to the mechanical and the water retention parts are then presented in subsequent sections. At the end, the typical response of the model is presented and the numerical simulations are compared the model simulation with the experimental results for unsaturated aggregated and saturated bonded soils.

2 COUPLED EFFECTS OF SUCTION AND SOIL STRUCTRE

The stress-strain behavior of unsaturated aggregated soils at the macro-scale has been studied using suction-controlled oedometer testing method [14]. Results of that study revealed three main class of effects: (i) soil structure effects describing the difference between reconstituted soil (with ‘intrinsic behavior’, after [16]) and aggregated soil at the same suction., (ii) intrinsic suction effects describing reconstituted soil at different suction values, and finally (iii) the coupled effects of soil structure and suction describing unsaturated aggregated soils at different suctions and their comparison to reconstituted soil results.

For the soil structure effects, the experimental results showed an apparent preconsolidation stress in aggregated soils, which depends not only on stress state and stress history, but also on the soil structure. Exhibiting an initial apparent overconsolidated state, aggregated soil appeared to have a normal consolidation line (NCL) located to the right side of that of reconstituted soil at the same suction. It was shown that the two curves tend to converge at higher stresses where the aggregated structure is obliterated (see in Figure 2).

Looking into the intrinsic suction effects, the main feature was found to be the increase of the effective apparent preconsolidation stress increases with suction. The term ‘effective’ will be further discussed in the mechanical constitutive framework in section 3.

Finally, as for the main coupled effect of suction and soil structure, experimental results showed that although the effective (apparent) preconsolidation stress increases with suction in both aggregated and reconstituted soils, the rate of this increase is higher for aggregated soil. In Figure 1, this behavior can be thought of as augmentation of the horizontal separation of the two curves as suction increases.

In addition to the above-mentioned macroscopic results, the pore-scale behavior of unsaturated aggregated soil has been also studied using the combination of mercury intrusion porosimetry, environmental electron scanning microscopy, and neutron computed tomography method [15]. Based on the obtained results, it has been suggested that the structural phenomenon of particle aggregation is the main cause of the macropore formation. As such, the macropores represent the actual state of the soil structure. Any degradation of structures due to mechanical loading or humidity variation results in closure of these extra pores, and brings the state of the soil closer to that of a reconstituted soil. As an important experimental finding, it was evidenced in neutron tomography tests that the change in the volume fraction of macropores is mainly associated with plastic deformations [17]. Those experimental evidences allow quantifying the soil structure in terms of macroporosity as a physical parameter and relate it to the plastic deformations as a state parameter [18,19].

3 MECHANICAL CONSTITUTIVE MODEL

3.1 Modeling framework

The proposed mechanical model, named ACMEG-2S, lies within the framework of hardening elastoplasticity and is based on the critical state concept [20]. It is originally built upon the model of Hujeux [21], and extends the ACMEG model of saturated reconstituted soils [22] to unsaturated structured state. The detailed mathematical formulation of the model can be found in [19]. The model considers the saturated reconstituted state as a reference state to which the suction and structure effects will be added.

The model uses the generalized effective stress defined here as the Bishop's effective stress [23] with the Bishop's coefficient being the degree of saturation [24, 25]:

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - p_a\boldsymbol{I} - S_r s\boldsymbol{I} \tag{1}$$

where $\boldsymbol{\sigma}'$ is the effective stress tensor, $\boldsymbol{\sigma}$ the total Cauchy stress tensor, S_r the degree of saturation, $s = p_a - p_w$ the matric suction with p_a and p_w being, respectively, the air and water pressures, and finally $\boldsymbol{I}$ is the identity tensor. Adopting the above constitutive stress provides a straightforward transition from saturated to unsaturated state owing to the uniqueness of the yield surface, constitutive stress, and the critical state line at the two states [26].

3.2 Model description

The model uses non-linear elasticity for the revisable part. Based on the experimental results, we assume that the elastic parameters are not affected neither by soil structure nor by partial saturation and are equal to those of the corresponding saturated reconstituted soil.

The plastic response in the model is governed by two plastic mechanisms, isotropic and deviatoric plastic mechanism. Following the concept of multi-mechanism plasticity [27], the total plastic strain increment is induced by the two corresponding dissipative processes. The two-invariant yield functions for the isotropic and the deviatoric mechanisms are:

$$f_{iso} = p' - p'_c r_{iso} = 0 \tag{2}$$

$$f_{dev} = q - Mp'\left(1 - b\ln\frac{p'd}{p'_c}\right) r_{dev} = 0 \tag{3}$$

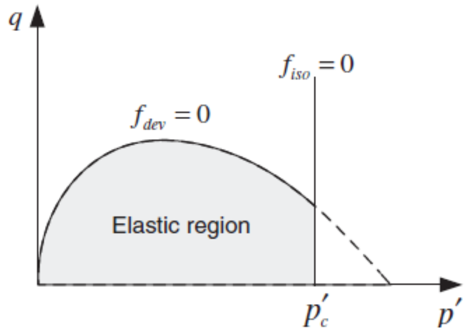

Figure 1 : Yield surfaces and elastic region in ACMEG-2S model

In these equations, p'_c is the apparent effective preconsolidation pressure accounting for the coupled effects of effects of suction and structure. It controls the size of the set union of the elastic regions given by the two yield functions in the stress plane, as depicted in Figure 1. The required material parameters are M, b, d, and those involved r_{iso} and r_{dev}.

Parameter M is the slope of the critical state line in the effective stress plane $q - p'$. This slope is neither affected by partial saturation [26] nor is influenced by the soil structure effects [6, among others]. Parameter b is a material parameter affecting the shape of the deviatoric yield surface. Parameter d, occasionally referred to as the spacing ratio [28], is the ratio of the saturated preconsolidation pressure over the saturated effective critical state pressure in the same yield surface for the soil (d fixed at 2.718 and 2.0 is the original and modified Cam-clay models, respectively). The two variables r_{iso} and r_{dev}.represent the degree of mobilization of isotropic and deviatoric plastic mechanisms, respectively, and allow a smooth transition from the elastic to plastic domain without abrupt change in the rate of deformation.

Postulating an identical shape of yield function for unsaturated aggregated and saturated reconstituted soil, parameters b and d are identical to their values in the reference model. Moreover, it is plausible for the mobilization process of plastic mechanisms to be independent of the suction and soil structure and to be governed directly by the provoked plastic strain. This implies no change in r_{iso} and r_{dev} compared with their reference value for reconstituted saturated soils. Accordingly, parameters of the yield limits are directly inherited from the intrinsic values of in the reference model. The model also assumes adopts the plastic flow rule of reference model for reconstituted soil which an associated the isotropic and non-associated for the deviatoric plastic mechanism.

3.3 Apparent preconsolidation pressure

The apparent effective preconsolidation pressure used in the expression of the yield functions (Eqs. 2 & 3) controls the size of the yield limits and it is the main element for taking into account the combined effects of suction and soil structure. The model uses an isotropic hardening rule that allows the change in size but not in the shape of the yield surface and, indeed, describes the evolution of the apparent effective preconsolidation pressure. We introduce the expression of the apparent effective preconsolidation pressure in the form [19]:

$$p'_c = \psi^{st} \psi^s p'_{c0} \tag{4}$$

where p'_{c0} is the reference effective preconsolidation pressure in saturated reconstituted soil, ψ^s is a function of suction accounting for the intrinsic primary suction-induced hardening effects as in reconstituted soils, and the function ψ^{st} introduces the soil structure effects including the mere soil structure effects and those coupled with suction.

The evolution of the reference effective preconsolidation pressure is governed by the intrinsic strain hardening (or softening) rule of the reference model, which is in the present case a volumetric plastic strain hardening rule of Cam-clay type. For the primary suction effects, the suction-induced hardening relation of reconstituted soil proposed by Nuth and Laloui [29] has been extended for the case of aggregated soils as

$$\psi^{s} = \begin{cases} 1 & ;\ 0 < s < s_e^1 \\ 1 + \gamma_s' \mathrm{Log}(s/s_e^1) & ;\ s_e^1 \le s < s_{ref} \\ 1 + \gamma_s \mathrm{Log}(s/s_e) & ;\ s \ge s_{ref} \end{cases} \tag{5}$$

where s_e and s_e^1 are the air entry value suction of the corresponding reconstituted soil and that of the micropores, respectively, γ_s and γ_s' are material parameters which are correlated through $\gamma_s' = \gamma_s \mathrm{Ln}(s_{ref}/s_e^1)/\mathrm{Ln}(s_{ref}/s_e)$, , and $s_{ref} > s_e$ is an arbitrary reference suction.

At the next step, the soil structure effects are introduced by recall the definition of the degree of soil structure R, as a physical parameter, which is the ratio of current macrovoid ratio, e^2, over its initial value , e_i^2 at the intact state (superscript 2 for macrovoids) [18]:

$$R = e^2/e_i^2 \tag{6}$$

The degree of soil structure is, indeed, an internal scaling parameter, which equals unity for an intact aggregated soil in the presence of macropores and zero for a fully destructured soil in their absence. Any structure degradation, irrespective of its cause, might alter the soil structure, the macropores, and consequently the degree of soil structure. This variable is then linked, as a state parameter, to the plastic strain through an equation of the form [18]

$$R = \exp(-\omega\varepsilon^D) \tag{7}$$

where ω is a material parameter controlling the rate of structure degradation with plastic deformation, and ε^D, referred to as destructuring strain, is an invariant of volumetric, deviatoric, or a combination of both plastic strain tensor [17,19].

Using Equation 6 and the compression plane of Figure 5, we can now derive the expression of ψ^{st} . Knowing that the physical definition of R implies $AA''/BB'' \approx R$, one can deduce the following expression for ψ^{st} [18]

$$\psi^{st} = (\psi_i^{st})^R \tag{8}$$

The soil structure function ψ^{st} should also account for the coupled effects of suction with the soil structure. As mentioned previously, the initial apparent preconsolidation pressure increases with suction at a higher rate in aggregated soil rather than in reconstituted soil. This corresponds to an increase in the horizontal distance between the two compression curves of aggregated and reconstituted soils in Figure 2; hence, a higher ψ^{st} as suction increases. Based on the experimental evidences [14], the following reversible function is proposed:

$$\psi^{st} = \psi_{\mathrm{iref}}^{st}\left(\frac{s + p_{at}}{s_{ref} + p_{at}}\right)^{n_{st}} \quad ;\ \psi_{\mathrm{iref}}^{st} \neq 1 \tag{9}$$

where p_{at} is the atmospheric pressure, $\psi_{\mathrm{iref}}^{st}$ is the initial reference value of the function for structured soil at the reference suction s_{ref}, and the exponent n_{st} is a material parameter.

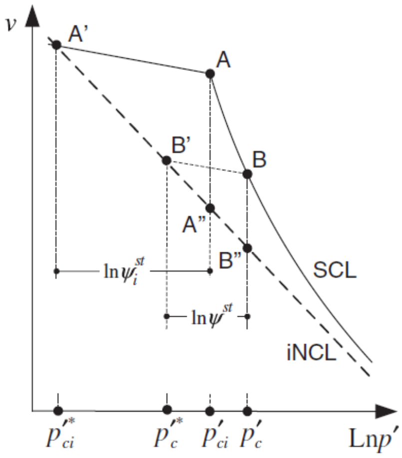

Figure 2 : Normal consolidation curves of aggregated (solid line) and reconstituted (dotted line) soils

The other coupling effect is related to the influence of suction on the rate of structure degradation, i.e. on parameter ω in Eq. 7. This parameter is also allowed to vary with suction to take into account the more brittle yielding of aggregated soils at higher suctions [19].

The coupled effects of suction on the apparent preconsolidation pressure in aggregated (structured) soils are illustrated in Figure 3. The abscissa is the ratio of apparent preconsolidation pressure over the saturated preconsolidation pressure in reconstituted sate, p'_c/p'^*_{c0}. The increase of apparent preconsolidation pressure due to intrinsic suction effect, $\Delta\psi_1$, given by Eq. 5, is represented by curve *a*. Multiplication of this curve with a reference soil structure function ψ^{st}_{ref} gives the curve *b*, which represents the increase in the apparent preconsolidation pressure due to intrinsic suction, $\Delta\psi_1$, and pure soil structure effects, $\Delta\psi_2$, without considering the suction-hardening of soil structure. Accounting for this latter effect by Eq. 9, the final evolution of apparent preconsolidation pressure with suction in aggregated soils is represented by curve *c*. The gray area between curves b and c in Figure 6, hence, corresponds to the gain in the apparent effective preconsolidation pressure due to the suction effects on the soil structure, $\Delta\psi_3$.

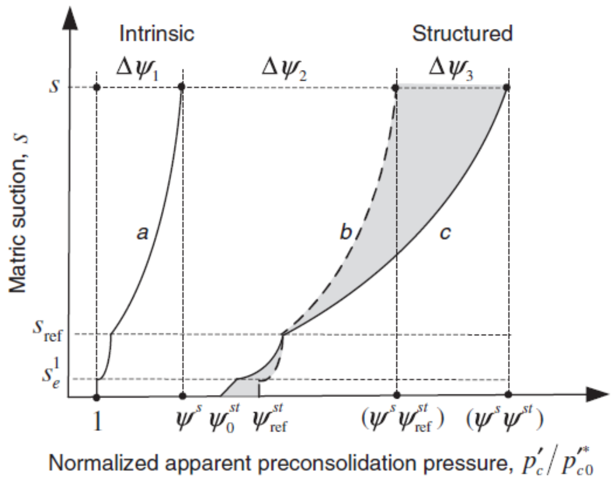

Figure 3 : Combined effects of suction and soil structure on the apparent isotropic preconsolidation pressure

3.4 General model formulation

The vectors of yield functions, plastic potentials, and non-negative plastic multipliers for two mechanisms can be written as

(10)

where the plastic strain tensor is obtained from the flow rule as

$$d\boldsymbol{\varepsilon}^{p} = \boldsymbol{\lambda}^{p}.\boldsymbol{g}, \quad \boldsymbol{g} = \frac{\partial \boldsymbol{G}}{\partial \boldsymbol{\sigma}'} \tag{11}$$

The plastic multipliers are determined using the Prager consistency equation for multi-dissipative plasticity [27] and satisfy the usual Kuhn–Trucker conditions

$$\mathrm{d}\boldsymbol{F} = \boldsymbol{f}: d\boldsymbol{\sigma}' - (H^{*} + H^{st}).\boldsymbol{\lambda}^{p} = 0, \ \ \boldsymbol{\lambda}^{p} \geq \mathbf{0} \text{ and } \boldsymbol{F} \leq \mathbf{0} \tag{12}$$

$$\boldsymbol{f} = \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{\sigma}'} \ , \quad \boldsymbol{H}^{*} = -\frac{\partial \boldsymbol{F}}{\partial p_c'^{*}} \cdot \frac{\partial p_c'^{*}}{\partial \boldsymbol{\lambda}^{p}} \ , \quad \boldsymbol{H}^{st} = -\frac{\partial \boldsymbol{F}}{\partial \psi^{st}} \cdot \frac{\partial \psi^{st}}{\partial \boldsymbol{\lambda}^{p}} \tag{13}$$

In the above relations, $\boldsymbol{H}^{*}$ is the generalized (primary suction effects included) hardening modulus corresponding to the reconstituted model, and $\boldsymbol{H}^{st}$ is the generalized hardening modulus arising from soil structure effects. For a constant, $\boldsymbol{H}^{st}<0$, i.e entries being negative, determines a softening due to structure degradation. However, to determine whether the material is in general hardening, softening, or showing a perfect plastic response, the sign of the total hardening modulus $\boldsymbol{H} = \boldsymbol{H}^{*} + \boldsymbol{H}^{st}$ should be considered.

Note that in the above form of consistency equation ds does not appear. This means that for any suction increments, all the suction-dependent variables are first updated with the new suction and then derivation is made with suction being held fixed. Hence, as proposed by Borja [30], there will be no return map on the suction during the numerical integrations.

Solving for the plastic multiplier yields

$$\boldsymbol{D}^{ep} = \boldsymbol{D}^{e} - \chi^{-1} \cdot (\boldsymbol{D}^{e}: \boldsymbol{g} \otimes \boldsymbol{f}: \boldsymbol{D}^{e}) \quad , \quad \chi = \boldsymbol{f}: \boldsymbol{D}^{e}: \boldsymbol{g} - \boldsymbol{H}^{*} + \boldsymbol{H}^{st} \tag{14}$$

where symbol $\otimes$ denotes the dyadic product of two tensors, and $\boldsymbol{D}^{ep}$ is the general elastoplastic constitutive tensor.

4 WATER RETENTION MODEL

The second part of the model describes the relation between suction and the degree of saturation. A number of well-established phenomenological water retention relations exist for non-deformable homogeneous porous media with single porosity [31, 32]. Such a relation, however, has been rarely investigated for porous media with multi-porosity [33, 34]. Total degree of saturation for double porous media in general is

$$S_r = \sum_{m=1,2} \Psi^{\mathrm{m}} S^{lm} \tag{14}$$

where S^{lm} is the local degree of saturation of the micro (m=1) and macropores (m=2), and Ψ^{m} is the volumetric pore fraction of micro/macropores over the entire pores. Assuming two distinct air entry suction values for micro and macropores, the total water retention curve of double porous media exhibits at least two points of inflection as in Figure 4.

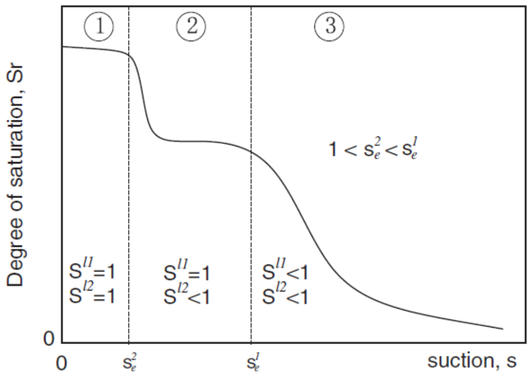

Figure 4 : Schematic water retention curve in soils with double porosity

Three different zones of saturation on this curve are zone 1 where both macro and micropores are saturated, zone 2 where micropores are saturated and macropores are unsaturated, and zone 3 where both macro and micropores are unsaturated.

In reality, however, the air entry value of macropores in aggregated soils is much lower than that of micropores. Therefore, it is plausible to assume that the macropores become drained at the very early stages of desaturation and the total degree of saturation reads

$$S_r \simeq \Psi^1 S^{l1} \tag{15}$$

As for the water retention equation governing S^{l1}, Durner [34] and Carminati et al. [35] considered a van Genuchten-type of equation [31] in non-deformable aggregated soil. A similar equation has been here considered and extended for deformable media by introducing the void ratio:

$$S^{l1} = \begin{cases} 1 & ;\ s \leq s_e^1 \\ \left[1 + \left(\alpha_s (e^1)^\beta s\right)^N\right]^{1/N-1} & ;\ s > s_e^1 \end{cases} \tag{16}$$

where α_s $[ML^{-1}T^{-2}]$ and N [-] are the van Genuchten's shape parameters, and the exponent β denotes the contribution of void ratio in the variation of degree of saturation. The way the deformation effects are included in this equation is similar to the one proposed by Gallipoli et al. [36], and allows variation of degree of saturation with induced deformation even at a constant value suction as evidenced in the experimental results [13, 14, 36, 37]. Note that in the above form of liquid retention law, the hydraulic hysteresis on drying and wetting paths [38] is not considered.

Using Eq. 6 for the degree of soil structure, we can write $\Psi^1 = 1 - e_i^2 R/e$ yielding the following expression of the total degree of saturation

$$S^{l1} = \begin{cases} 1 & ;\ s = 0 \\ 1 - e_i^2 R/e & ;\ s_e^1 > s > 0 \\ (1 - e_i^2 R/e) \cdot \left[1 + \left(\alpha_s (e - e_i^2 R)^\beta s\right)^N\right]^{1/N-1} & ;\ s > s_e^1 \end{cases} \tag{17}$$

The degree of soil structure in the above equation, as a state parameter, is linked to the plastic strains through (21). Accordingly, the above water retention model is coupled with the mechanical model through the degree of soil structure, void ratio and also, the suction and the degree of saturation present in the expression of the effective stress.

5 NUMERICAL SIMULATIONS

The model has been used for numerical simulation of experimental results. Numerical integration of the constitutive equations was made using an existing driver of constitutive equations [39] modified for the equations of ACMEG-2S. Input data includes the material properties, material state and imposed loading. After initialization of parameters and stress states, the model uses a return mapping-type algorithm in which stress and strains of a given step are predicted based on elastic analysis and then corrected using plastic iteration.

The model has been examined for its capability in reproducing the experimental result of suction-controlled oedometer test on unsaturated aggregated Bioley silty clay given in [14]. The results that are presented here (samples USS03) correspond to oedometric compression at the maximum suction of circa 500 kPa. The model parameters are determined based on suction-controlled oedometer tests on corresponding unsaturated reconstituted samples, and some mercury intrusion tests (MIP). Values of Ψ_i^2 have been deduced based on the aggregate porosity 22% obtained from MIP tests of single aggregate [15]. The reference suction is 500 kPa; and the initial soil structure function at this suction $\psi_i^{st} = 175.63$.

This test involves two phases: first is the increase of suction from 50 to 500 kPa, and second is the mechanical loading and unloading where the vertical net stress varies between 15 and 3000 kPa under the constant suction. Figure 7(a) shows the evolution of the degree of soil structure, R, as the effective stress increases. R reduces from 1 at the initial state to 0.26 at the end of the compression, remaining constant during unloading. As observed in Figure 7(b), the model successfully reproduces the effective stress-strain response of the sample.

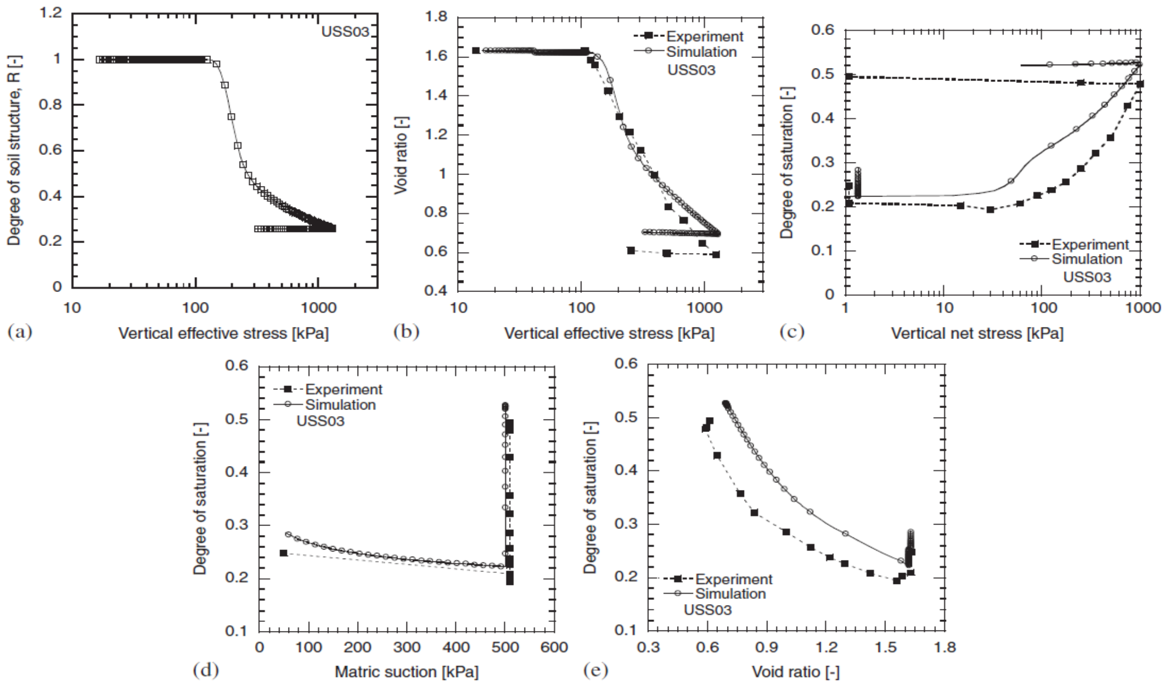

Figure 5 : Model simulation and experimental results for unsaturated oedometer test on aggregated Silty clay

Thanks to the modified water retention relation and its coupling with deformation, the model addresses the main features in the evolution of degree of saturation during the test (Figure 17(c)). For the early steps, despite a relatively low value of initial suction (si=50kPa), the model gives a low degree of saturation of about 0.29. This is due to the existence of empty macropores. Similar to the experimental results, simulations also show an insignificant decrease of degree of saturation due to suction increase. During the subsequent mechanical loading at constant suction, however, the model predicts the strong increase of the degree of saturation because of macropore closure. The good correlation between the simulated and experimental data for this phenomenon can be better observed in Figures 7(d) and 7(e) where the evolution of degree of saturation is expressed in terms of suction and void ratio.

6 CONCLUSIONS

A coupled water retention–mechanical constitutive model, named ACMEG-2S, was proposed for unsaturated soils with double porosity. It incorporates the inter-particle bonding, fabric and partial saturation effects in a single framework. The model builds upon multi-scale experimental results and has two interconnected parts: mechanical and water retention parts.

The mechanical part of the model lies within the framework of hardening elastoplasticity and is based on the critical state concept. It uses non-linear elasticity and two isotropic and deviatoric plastic mechanisms. Using the generalized Bishop's effective stress with the Bishop's parameter being the degree of saturation, the model allows a straight forward transition from saturated to unsaturated condition. Partial saturation is considered through the primary effects on soil matrix, and secondary effects coupled with soil structure. A new apparent effective preconsolidation pressure has been introduced which depends not only on stress state and history but also on soil structure and suction. The soil structure is quantified in terms of macropore volume fraction using an experimentally-based parameter, called degree of soil structure, the evolution of which is linked to the plastic strains.

In the water retention part of the model, an improved relation has been proposed accounting for deformation and double porosity effects. The two parts of the model are fully coupled through the expression of the effective stress and the degree of soil structure.

Numerical simulations showed that the model can successfully address the main features including the non-linear stress–stress relationship during the virgin compression and the increase of degree of saturation during compression at constant suction. The proposed model provides an efficient tool for coupled constitutive modeling of unsaturated structured soils behavior in geotechnical problems.

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