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On understanding hydromechanics of unsaturated soils: A novel model accounting for fully coupled hydro-mechanical behavior including hydraulic hysteresis

Sur la compréhension de l'hydromécanique des sols non saturés : un nouveau modèle prenant en compte le comportement hydromécanique entièrement couplé, y compris l'hystérésis hydraulique

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ABSTRACT: Unsaturated soils are complex three phase media whose phases interact with one another under mechanical or hydraulic forces. While degrees of saturation of the two fluid phases have a decisive role on the mechanical properties of soil, in return, any changes associated with the mechanical stress-field also affect the degrees of saturation through changes in suction. Such a coupled behavior becomes the key point in understanding unsaturated soils and developing accurate constitutive models. Although there have been many such studies in the last three decades, there still needs experimental and theoretical works to be done for understanding unsaturated soil behavior. In this study, a novel constitutive model accounting for two-way coupled hydro-mechanical behavior of unsaturated soils including hydraulic hysteresis is proposed. On the mechanical side, elasto-plastic behavior is governed by the classical plasticity framework yielding the stress-strain relationship, whereas on the hydraulic side, water retention behavior is governed by the soil-water characteristic curve incorporating the irreversible volumetric deformations due to wetting-drying cycles. The model parameters introduced into the theoretical framework of the model for characterizing the hydro-mechanical behavior are measured directly from classical and unsaturated triaxial tests. Subsequently, predicted model results in terms of isotropic compression are calibrated with a set of suction-controlled drained triaxial tests. The proposed model contributes to enhancing our knowledge on fully coupled hydro-mechanical behavior of unsaturated soils.

RÉSUMÉ : Les sols non saturés sont des milieux triphasés complexes dont les phases interagissent les unes avec les autres sous des forces mécaniques ou hydrauliques. Alors que les degrés de saturation des deux phases fluides ont un rôle décisif sur les propriétés mécaniques du sol, en retour, tout changement associé au champ de contrainte mécanique affecte également les degrés de saturation par des changements de succion. Un tel comportement couplé devient le point clé pour comprendre les sols non saturés et développer des modèles constitutifs précis. Bien qu'il y ait eu de nombreuses études de ce type au cours des trois dernières décennies, il reste encore des travaux expérimentaux et théoriques à faire pour comprendre le comportement des sols non saturés. Dans cette étude, un nouveau modèle constitutif tenant compte du comportement hydromécanique couplé bidirectionnel des sols non saturés, y compris l'hystérésis hydraulique, est proposé. Côté mécanique, le comportement élasto-plastique est régi par le cadre de plasticité classique donnant la relation contrainte-déformation, tandis que du côté hydraulique, le comportement de rétention d'eau est régi par la courbe caractéristique sol-eau intégrant les déformations volumétriques irréversibles dues au mouillage. cycles de séchage. Les paramètres du modèle introduits dans le cadre théorique du modèle de caractérisation du comportement hydromécanique sont mesurés directement à partir d'essais triaxiaux classiques et non saturés. Par la suite, les résultats du modèle prédit en termes de compression isotrope sont calibrés avec un ensemble d'essais triaxiaux drainés à succion contrôlée. Le modèle proposé contribue à améliorer nos connaissances sur le comportement hydromécanique entièrement couplé des sols non saturés.

KEYWORDS: Constitutive modeling, hydraulic hysteresis, hydro-mechanical coupling, suction, unsaturated soils.

1 INTRODUCTION

Classical soil mechanics has mostly focused on saturated soils even though the natural soils above ground water table are actually formed in three phases including the air-phase partially filling in the voids. Due to a potential rise in the water content of soils in the vadose zone, current geotechnical practice that models unsaturated soil mechanical properties as though they pertain to fully saturated states leads to unsafe design. Saturation of natural soil samples in the laboratory, which would otherwise be partially saturated with natural in-situ water levels, softens the soil resulting in an undesired over-design. That is, unsaturated soil layers in the field are not expected to stay fully saturated during seasonal fluctuations of ground water level. The particulate, multiphase, heterogeneous, and nonlinear nature of unsaturated soils (UNSAT) complicates the factors affecting the hydromechanical behavior of such soils.

The development of "unsaturated soil mechanics" has trailed behind that of "saturated soil mechanics" and the study of UNSAT has gained importance only in the last few decades. Despite the fact that many research studies on UNSAT have been conducted since the early 1990s, more experimental and theoretical work is required to fully understand the UNSAT hydro-mechanical behavior. Starting from the early works of Aitchison & Donald 1956, Bishop 1059, Fredlund & Morgenstern 1976, Lloret & Alonso 1980 for more than half a century ago, attention is given to the constitutive modeling of UNSAT, which finds a wide range of applications for natural soils above ground water table. The well-known Barcelona Basic Model by Alonso et al. 1990, is the pioneering study that brings together previously disparate ideas into a sound elasto-plastic framework. Subsequently, following constitutive models are developed with varying degrees of success based on diverse theoretical assumptions (Kohgo et al. 1993, Buisson & Wheeler 2000, Vaunat et al. 2000, Wheeler et al. 2003, Gallipoli et al. 2003, Khalili et al. 2005, Russell & Khalili 2006, Mac et al. 2017, Arroyo & Rojas 2019, Kodikara et al. 2020, Cao et al. 2021). The two main groups of studies that are distinguished based on their stress state are the first major departure from these constitutive models. One group assumes that stress can be described using a single Bishop effective stress (Bishop 1959, Kohgo et al. 1993, Gallipoli 2000, Jommi 2000, Wheeler et al. 2003, Sun et al. 2008). The other group contends that the UNSAT stress state (Fredlund & Morgenstern 1977, Alonso et al. 1990, Gens et al. 2006, Fredlund & Pham 2007, Sheng et al. 2008, Sheng &

Zhou 2011, Ng et al 2020) is governed separately by the modified total stress known as the net stress, p, and matric suction, s. The first is known as the "effective stress approach" while the second is known as the "independent stress variables approach". It is perhaps an agreement in the field that each stress state offers advantages over the other (d'Onza et al 2011, Sheng 2011, Arroyo & Rojas 2019).

Aside from the stress state, a significant concern with UNSAT is the presence of hydraulic hysteresis in their water retention behavior, which has a significant impact on their mechanical behavior. Hydraulic hysteresis is an important soil-water characteristic feature resulting from the water retention behavior governing the relationship between degree of saturation and suction in UNSAT. Both geotechnical engineers and soil physicists (Hillel 1971, Fredlund & Rahardjo 1993, Sheng et al. 2008) study soil-water characteristic behavior. The soil pore water, according to Barbour 1998, Romero et al. 1999 and Vaunat et al. 2000 is related to two mechanisms: water that may readily flow through the pores and water that clings to the soil particles. These two mechanisms are independent, in that the former is related to both the static response of the soil and suction (Vaunat et al. 2000), while the latter manifests itself in experimental methods where the relative humidity is controlled. The void ratio and mean net stress are found to affect the water retention behavior in related experiments. Additionally, adjusting the mean net stress changes the water content (Sheng et al. 2008, Sheng 2011, Zhou et al. 2012). Many such models simply distinguish between elastic and elastoplastic behavior and assign constant adsorption/desorption rates to these sections (Wheeler et al. 2003, Sheng et al. 2008, Gallipoli 2012, Wong & Masin 2014). Even though this is a simple strategy, it does not enable a seamless transition to saturated state (Ng et al. 2020). Using the bounding surface theory to create their water retention models, several researchers suggest less common approaches to solve this problem (Li 2005, Gallipoli 2015, Zhou et al. 2015).

Wheeler 1996 and Dangla et al. 1997 are among the first to point out the importance of including a hydraulic component in the UNSAT constitutive model. The model of Vaunat et al. 2000, on the other hand, is one of the first hydro-mechanically coupled models (Gens et al. 2006). This model incorporates BBM's concept of solid skeleton strains with an additional parameter named "hydraulic strain" ($\boldsymbol{\varepsilon}_w$), which is equal to the expression commonly known as "volumetric water content" in terms of variations in pore water volume, θ. Since then, there have been many attempts to explain the hydromechanical coupling of UNSAT (Wheeler et al. 2003, Sheng et al. 2004, Chen 2007, Sun et al. 2007, Sun & Xiang 2007, Sheng & Zhou 2011, Zhou et al. 2018, Arroyo & Rojas 2019, Kodikara et al 2019). Wheeler et al. 2003 uses two coupling parameters and the effective stress as well as the modified suction without a water retention function. Sheng & Zhou 2011 provide a simple yet accurate model based on independent stress factors, with the necessary equations derived from the intrinsic relationships. Zhou 2017, who takes a different approach to unsaturated behavior, uses the degree of saturation, S_r, as a separate variable and proposes a stress-S_r volume change relationship. Liu et al. 2021 investigates the hydromechanical coupling by incorporating heat effects into their constitutive model. Their study is mostly based on Wheeler et al.'s 2003 in its hydraulic and mechanical parts. Kodikara et al. 2020 offer one of the most recent hydromechanically coupled models, whose mechanical stress-strain relationship is based on the BBM and which successfully simulates many laboratory experiments in a coupled manner.

In this study, a hydromechanically coupled elasto-plastic model is developed for unsaturated soils. The proposed model includes hydraulic hysteresis and is able to predict the degree of saturation changes caused by net stress and suction. A model parameter is used to define the essential relationship between the net stress and the degree of saturation, which can be obtained by unsaturated triaxial tests. The change in void ratio on the water retention behavior is given special consideration.

2 HYDRO-MECHANICS OF UNSATURATED SOILS

The particulate and three-phase structure of UNSAT causes them to exhibit coupled behavior in a way that the water content and the void ratio can be affected by changes in both suction and net stress. The mechanical component of the coupled response is related to total strain, while the hydraulic component governs the effect of volumetric water content on the water retention behavior. The essence of unsaturated soils is governed by such a complex behavior, which should be described by a phenomenological constitutive model that functions at the elemental level.

2.1 *The mechanical component of coupled behavior*

In this study, independent stress variables approach is adopted as it allows more control over the constitutive relation by separating the sources of stress on the soil as net stress and suction. Therefore, the mechanical behavior of UNSAT is governed by the incremental change in the strain field of solid skeleton in terms of total strain (i.e. volumetric and deviatoric) and corresponding stress state in terms of net stress and suction.

In this study, the total strain is split into two parts according to the sources of those strains. The strain caused by net stress is represented by a subscript "m" and the strain that is caused by suction is represented by a subscript "h". Both parts have elastic and plastic components as well. Therefore we write:

$$\varepsilon = \varepsilon_m + \varepsilon_h = \varepsilon_m^e + \varepsilon_m^p + \varepsilon_h^e + \varepsilon_h^p \quad (1)$$

The elastic component of the total strain can be written in terms of stresses as:

$$d\varepsilon^e = d\varepsilon_m^e + d\varepsilon_h^e = (D^e)^{-1} d\bar{\sigma} + \left(\widehat{D_h^e}\right)^{-1} ds \quad (2)$$

where D^e is the elastic constitutive matrix and $\widehat{D_h^e}$ is the elastic modulus for the suction-strain relationship. Rearranging this equation yields the following relations:

$$d\bar{\sigma} = D^e(d\varepsilon - d\varepsilon^p) + D_h^e\, ds \quad (3)$$

$$D_h^e = -D^e \frac{\kappa_s}{v(s+p_a)} \quad (4)$$

The plastic strain increment in Eq. 3 can be separated into its components as:

$$d\bar{\sigma} = D^e\left(d\varepsilon - d\varepsilon_m^p - d\varepsilon_h^p\right) + D_h^e ds \quad (5)$$

where the plastic strain increment caused by suction is defined as:

$$d\varepsilon_h^p = \left(\widehat{D_h^p}\right)^{-1} ds \quad (6)$$

Substituting Eq. 6 into Eq. 5 and rearranging the equation yields:

$$d\bar{\sigma} = D^e\left(d\varepsilon - d\varepsilon_m^p\right) + \left(-D^e\left(\widehat{D_h^p}\right)^{-1} + D_h^e\right) ds \quad (7)$$

In Eq. 7, the multiplier of the suction increment can simply be written as:

$$D_h^{ep} = D_h^e + D_h^p \quad (8)$$

where,

$$D_h^p = -D^e \left(\widehat{D_h^p}\right)^{-1} \tag{9}$$

The final form of the stress-strain-suction relationship becomes,

$$d\bar{\sigma} = D^e\left(d\varepsilon - d\varepsilon_m^p\right) + D_h^{ep} ds \tag{10}$$

For the sake of simplicity, volumetric relations of the BBM is adopted at this point. Since it is also defined in terms of independent stress variables, it links the change in void ratio independently to the increments of net mean stress and suction as:

$$dv_m = -\kappa \frac{dp}{p} \tag{11}$$

$$dv_s = -\kappa_s \frac{ds}{(s+p_{atm})} \tag{12}$$

where the increments of the specific volume, dv, net mean stress, dp and suction, ds, are the main variables. The elastic constants, κ, κ_s, along with the reference pressure, p_{atm} are used to define the basic elastic constitutive relations of the proposed model.

The yield surface of the model is similar to the Modified Cam-Clay model for the saturated state but now varies with the suction (Figure 1). The yield stress values for isotropic compression (p_0) and extension (p_s) depend on the current suction value, which controls the size of the yield surface, which is written as:

$$f(\bar{\sigma}, h) = q^2 - M^2(\bar{p} + p_s)(p_0 - \bar{p}) = 0 \tag{13}$$

where h is the 'hardening parameter' and p_0 is the preconsolidation stress (its projection for saturated state is marked with an asterisk). In BBM, the hardening parameter p_0 is obtained with the plastic volumetric strain and suction:

$$\frac{dp_0}{p_0} = \frac{v}{\lambda(s) - \kappa}\, d\varepsilon_v^p \tag{14}$$

$$\left(\frac{p_0}{p^c}\right) = \left(\frac{p_0^*}{p^c}\right)^{[\lambda(0)-\kappa]/[\lambda(s)-\kappa]} \tag{15}$$

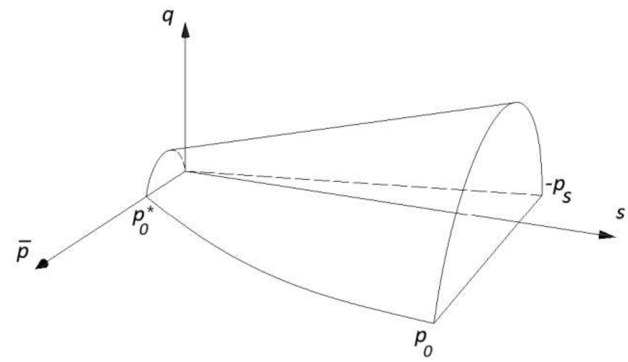

Figure 1. Model yield surfaces and their dependence on suction

According to the classical plasticity theory, the consistency condition for the yield surface Eq. 12 is written as:

$$df = \frac{\partial f}{\partial \bar{\sigma}}^T d\bar{\sigma} + \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial \varepsilon_m^p}^T d\varepsilon_m^p + \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial s}^T ds + \frac{\partial f}{\partial p_s}\frac{\partial p_s}{\partial s}^T ds = 0 \tag{16}$$

which includes both suction and net stress terms.

Considering a non-associated flow rule, we write:

$$d\varepsilon_m^p = d\lambda_m \frac{\partial g}{\partial \bar{\sigma}} \tag{17}$$

with $d\lambda_m$ being the plastic multiplier. Even though the above formulation is derived for a non-associated flow rule, $f=g$ can be embraced if associated flow rule is preferred. When Eq. 10 and 17 are introduced in Eq. 16, we get:

$$df = \frac{\partial f}{\partial \bar{\sigma}}^T \left[D^e\left(d\varepsilon - d\lambda_m \frac{\partial g}{\partial \bar{\sigma}}\right) + D_h^{ep}\, ds\right] + \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial \varepsilon_m^p}^T d\lambda_m \frac{\partial g}{\partial \bar{\sigma}} + \left(\frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial s}^T + \frac{\partial f}{\partial p_s}\frac{\partial p_s}{\partial s}^T\right) ds = 0 \tag{18}$$

where $d\lambda_m$ can be obtained as:

$$d\lambda_m = \frac{\frac{\partial f}{\partial \bar{\sigma}}^T D^e\, d\varepsilon + \left(\frac{\partial f}{\partial \bar{\sigma}}^T D_h^{ep} + \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial s}^T + \frac{\partial f}{\partial p_s}\frac{\partial p_s}{\partial s}^T\right) ds}{\frac{\partial f}{\partial \bar{\sigma}}^T D^e \frac{\partial g}{\partial \bar{\sigma}} - \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial \varepsilon_m^p}^T \left\|\frac{\partial g}{\partial \bar{\sigma}}\right\|} \tag{19}$$

Now, substituting Eq. 19 into Eq. 17 and rewriting Eq. 10 yields:

$$d\bar{\sigma} = D^e\left[I - \frac{\partial g/_{\partial \bar{\sigma}}\, \partial f/_{\partial \bar{\sigma}}^{\ T} D^e}{\frac{\partial f}{\partial \bar{\sigma}}^T D^e \frac{\partial g}{\partial \bar{\sigma}} - \frac{\partial f}{\partial h}\frac{\partial h}{\partial \varepsilon_m^p}^T \frac{\partial g}{\partial \bar{\sigma}}}\right] d\varepsilon + \left[\frac{-D^e\left(\frac{\partial f}{\partial \bar{\sigma}}^T D_h^{ep} + \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial s}^T + \frac{\partial f}{\partial p_s}\frac{\partial p_s}{\partial s}^T\right)\frac{\partial g}{\partial \bar{\sigma}}}{\frac{\partial f}{\partial \bar{\sigma}}^T D^e \frac{\partial g}{\partial \bar{\sigma}} - \frac{\partial f}{\partial p_0}\frac{\partial p_0}{\partial \varepsilon_m^p}^T \frac{\partial g}{\partial \bar{\sigma}}} + D_h^{ep}\right] ds \tag{20}$$

2.2 *The hydraulic component of coupled behavior*

To define the hydraulic component, we employ the chain rule to extend the following intrinsic equation (Eyüpgiller & Ülker 2019):

$$\theta = S_r n \tag{21}$$

$$d\theta = d(S_r n) = S_r * dn + n dS_r \tag{22}$$

$$d\theta = S_r\left(\frac{\partial n}{\partial \varepsilon_{vm}} d\varepsilon_{vm} + \frac{\partial n}{\partial s} ds\right) + n\left(\frac{\partial S_r}{\partial \varepsilon_{vm}} d\varepsilon_{vm} + \frac{\partial S_r}{\partial s} ds\right) \tag{23}$$

Eq. 23 can be rewritten as:

$$d\theta = \left[n\, {}^{\partial S_r}/_{\partial \varepsilon_{vm}} - {}^{S_r}/_{(1+e)}\right] d\varepsilon_{vm} + \left(S_r\, {}^{\partial n}/_{\partial s} + n\, {}^{\partial S_r}/_{\partial s}\right) ds \tag{24}$$

where n is the porosity, e is void ratio. Eq. 24 can be written in another way to calculate the increment of S_r:

$$dS_r = \left({}^{1}/_{n}\, {}^{\partial \theta}/_{\partial \varepsilon_{vm}} - {}^{\theta}/_{n^2}\, {}^{\partial n}/_{\partial \varepsilon_{vm}}\right) d\varepsilon_{vm} + \left({}^{1}/_{n}\, {}^{\partial \theta}/_{\partial s} - {}^{\theta}/_{n^2}\, {}^{\partial n}/_{\partial s}\right) ds \tag{25}$$

The relationship between suction and the degree of saturation is commonly expressed by using a soil-water retention curve (SWRC). It can be seen that the coefficient of the increment of suction in the second term of Eq. 25 provides the necessary link between the degree of saturation and suction, therefore, this coefficient can be extracted from a relevant SWRC. We can rewrite Eq. 25 and present the SWRC term as the partial derivative as:

$$dS_r = \left[{}^{1}/_{n} * {}^{\partial\theta}/_{\partial\varepsilon_{vm}} + {}^{S_r}/_{e}\right] d\varepsilon_{vm} + \left({}^{\partial S_r}/_{\partial s}\right)_{SWRC} ds \qquad (26)$$

In order to complete the hydraulic component of the formulation, the present study requires an SWRC model that includes the effects of changing void ratios on the water retention behavior, such as Gallipoli et al. 2015. It needs to be mentioned here that based on our investigation of many available experimental results, we believe that the evaluation of the partial derivative, $d\theta/d\varepsilon_{vm}$ becomes too complex to do analytically as multiple causes factor in. Instead, the following empirical expression is employed in this study:

$$ {}^{\partial\theta}/_{\partial\varepsilon_{vm}} = -{}^{B}/_{Sr} \qquad (27)$$

where, B is a material parameter, which is related to the predisposition of the soil under drainage and can be obtained from isotropic compression tests in which the amount of drained pore water volume is measured. Applying Eq. 27 into Eq. 26, yields the final form of the hydraulic component of the proposed model:

$$dS_r = \left[{}^{S_r}/_{e}\left(1 - {}^{B}/_{nS_r}\right)\right] d\varepsilon_{vm} + \left({}^{\partial S_r}/_{\partial s}\right)_{SWRC} ds \qquad (28)$$

3 MODEL PREDICTIONS

Two sets of drained isotropic compression tests were simulated using the proposed model. Firstly, one test in each set is chosen as a calibration test, on which the model parameters are obtained. Then, rest of the tests in the sets are simulated by using the model parameters that are obtained from the calibration simulations.

The first set of unsaturated drained triaxial (CD) tests to simulate the isotropic compression behavior is conducted on Mersin silt. The experimental data are obtained from our earlier work of Eyüpgiller et al. 2021 along with Ahmadi-Naghadeh 2016 (Figure 2). The former is used as the calibration simulation (Figure 3), while the latter is used to verify with the previously acquired model parameters (Figure 4). Both are conducted under the same constant suction of 100 kPa and loaded with up to 400 kPa of net stress. The SWRC model of van Genuchten 1980 is found to be sufficient for these tests. The proposed model captures the general hydromechanical response of the soil well. The error observed in the results of hydraulic part is about 1%. Table 1 shows the parameters used in this simulation, where the parameter values are listed according to the initial void ratio counterparts of the respective tests.

Table 1. Parameters used in simulations of Mersin Silt

Model parameters		van Genuchten parameters	
λ	0.086, 0.028	vG_m_d	0.018
κ	0.032, 0.008	vG_n_d	60
λ_s	0.008	vG_a_d	20
k	0.4	vG_m_w	0.022
e_0	1.83, 1.73	vG_n_w	45
p_0 (kPa)	90, 120	vG_a_w	9
B	0.0652		

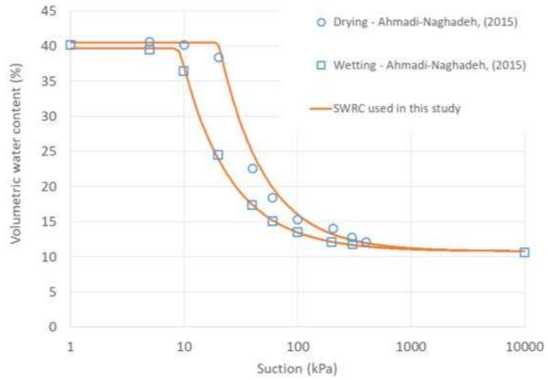

Figure 2. The SWRC of the Mersin silt used in this study and its comparison to the experimental results Ahmadi-Naghadeh 2016

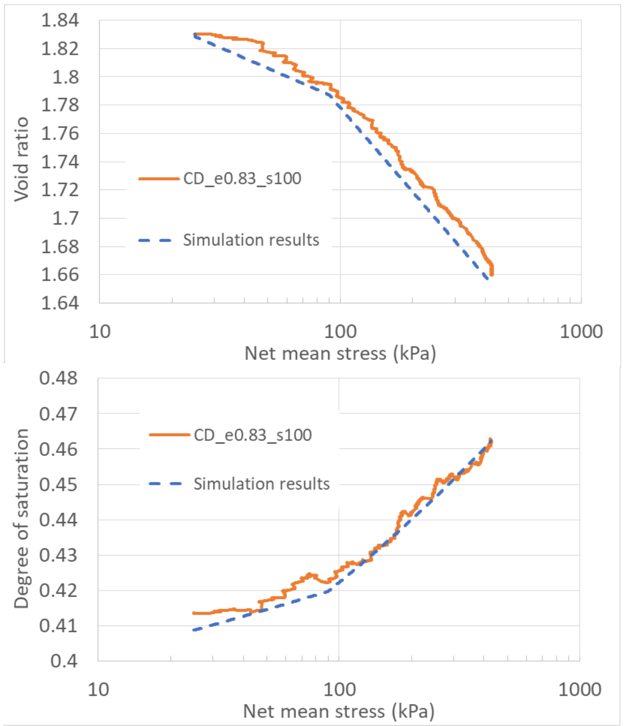

Figure 3. Calibration of the model parameters on the drained isotropic compression test of Eyüpgiller et al. 2021

The second set of experiments shows the model capacity in various suction and initial degree of saturation levels, which also emphasizes its ability to capture the hydraulic hysteresis. Three bentonite-kaolin mixtures with similar initial void ratios are subjected to various constant suction values (100-200-300 kPa) and then isotropically loaded and unloaded. The water retention behavior in terms of suction-water content relationship is adopted from Gallipoli 2012. Parameters of the current model and the SWRC model are given in Table 2.

Table 2. Parameters used in simulations of Sharma 1998

Model parameters		Gallipoli 2012 parameters	
λ	0.18, 0.16, 0.14	m	0.0333
κ	0.0015	n	4.53
λs	0.008	Ψ	6.62
k	0.4	ω_{wet}	59.3
e_0	1.32, 1.27, 1.27	ω_{dry}	188
p_0 (kPa)	35, 50, 55	m_{sc}	0.161
s (kPa)	100, 200, 300	n_{sc}	0.621
B	0.191	Ψ_{sc}	10

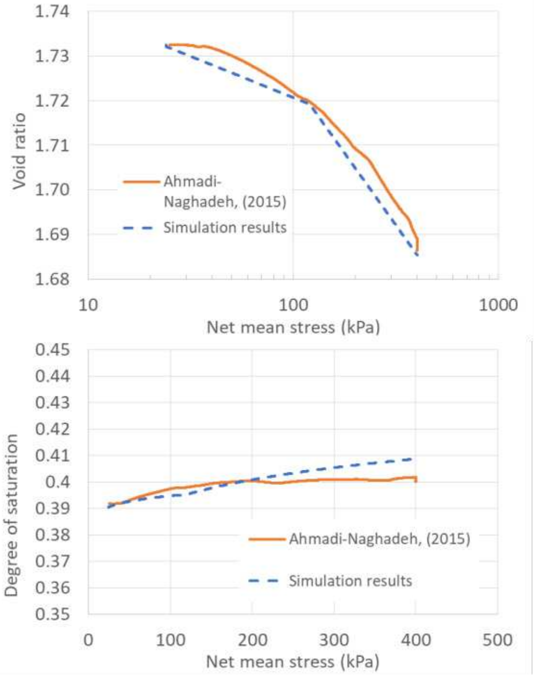

Figure 4. Simulation of the drained isotropic compression test of Ahmadi-Naghadeh

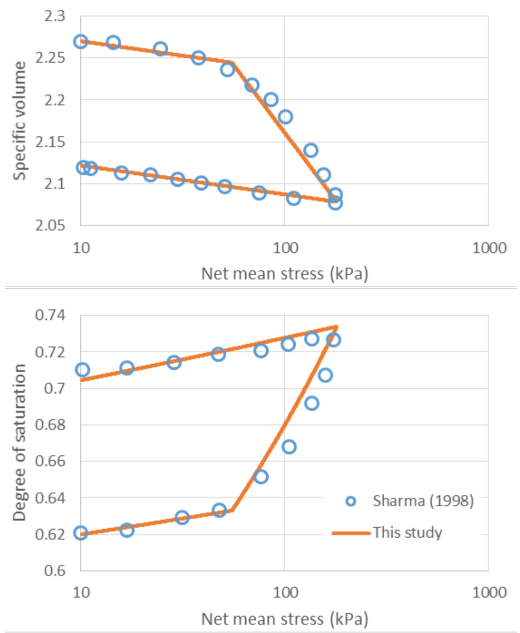

Figure 5. The isotropic compression test with s=300 kPa is used for the calibration of the model parameters (Sharma 1998)

2 CONCLUSIONS

In this study, a novel constitutive model accounting for two-way coupled hydro-mechanical behavior of unsaturated soils including hydraulic hysteresis is proposed. The unsaturated soil behavior is governed by both mechanical and hydraulic components. The mechanical part is governed by the elasto-plastic behavior using the modified Barcelona Basic Model based upon the classical plasticity framework, which yields the stress-strain relationship, whereas the hydraulic part is governed by the water retention behavior in terms of the soil-water retention curve. The proposed model incorporates the irreversible volumetric deformations due to wetting-drying cycles. The model also predicts the isotropic compression behavior well accounting for the effect of both suction and net stress on the compression of unsaturated soils.

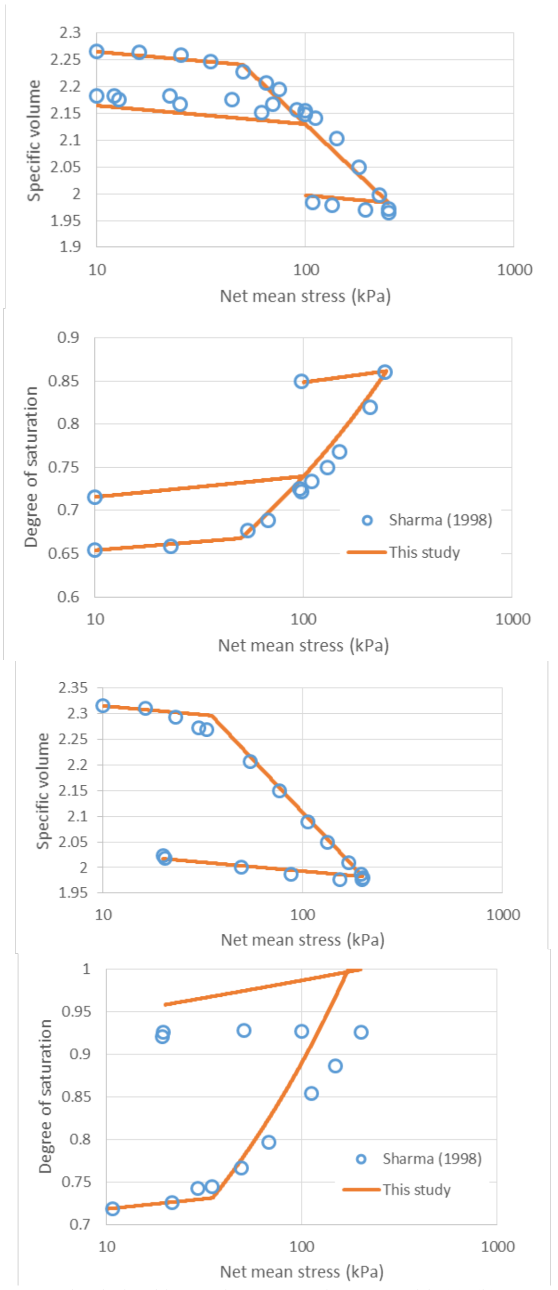

Figure 6. The drained isotropic compression tests with (a)-(b) s=200 kPa and (c)-(d) s=100 kPa and the comparison of the simulation results of Sharma 1998

3 ACKNOWLEDGEMENTS

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