Deformation induced by wetting: a simple model

Francesca Casini

Abstract: This paper presents a simple model for predicting the deformation induced by wetting. The objective is to quantify the deformation induced by saturation of an unsaturated layer of homogeneous soil, causing variation of the initial void ratio and gravimetric water content. The soil is a low-plasticity silty sand. A simple expression for the normal compression line (NCL), which depends on the parameter χ and one more parameter, will be proposed. The model may capture the progressive degradation induced by loading and wetting by linking the dependency of NCL by the parameter χ and water retention curve by porosity.

Key words: constitutive relations, laboratory tests, partial saturation, deformation, water retention curve.

Résumé : Cet article présente un modèle simple pour la prédiction de la déformation induite par le mouillage. L'objectif est de quantifier la déformation induite par la saturation d'une couche de sol homogène non saturée, causant ainsi des variations de l'indice des vides initial et de la teneur en eau gravimétrique initiale. Le sol est un sable silteux à faible plasticité. Une expression simple de la ligne de compression normale (LCN), qui dépend du paramètre χ et d'un autre paramètre, est proposée. Le modèle permet d'intégrer la dégradation progressive causée par le chargement et le mouillage, en reliant la dépendance de la LCN avec le paramètre χ et la courbe de rétention d'eau avec la porosité.

Mots-clés : relations constitutives, essais en laboratoire, saturation partielle, déformation, courbe de rétention d'eau.

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Introduction

The prediction of settlement induced by wetting is of particular importance in ground engineering. To mitigate sudden displacement during the life of a structure or of a natural deposit, it is important to predict the deformation of soils induced by the wetting process as unsaturated soils may either swell or shrink when they experience a wetting path. This is a function of the initial conditions in terms of void ratio and water content (e.g., from experimental investigations: Lawton et al. 1989; Gens et al. 1995; Ferber et al. 2008; Muñoz-Castelblanco et al. 2011; Vilar and Rodrigues 2011; also from theoretical point of view: Alonso et al. 1990; Or 1996; Lu et al. 2010).

The Barcelona basic model, developed by Alonso et al. (1990), was the first to capture certain features of unsaturated soil behaviour. In the last three decades, many constitutive models have been proposed to also achieve this (e.g., Jommi and di Prisco 1994; Alonso et al. 1999; Gallipoli et al. 2003*a*; Tamagnini 2004; Sun et al. 2008; Alonso et al. 2010; Mašín 2010). This modern trend highlights the importance of taking the dual dependency of mechanical behaviour and retention properties into account. In particular, a lot of work has been done in the last decade on the dependency of the water retention curve on the void ratio (Romero and Vaunat 2000; Gallipoli et al. 2003*b*; Nuth and Laloui 2008; Tarantino 2009; Romero et al. 2011; Casini et al. 2012).

This paper presents a simple model to evaluate the deformation induced by wetting (under oedometric conditions) knowing the saturated normal compression line (NCL) and adopting one more parameter for quantifying the rate of change of effective stress caused by variation of parameter χ. As pointed out by Gens et al. 2006, the constitutive models of unsaturated soils are classified in three different classes depending on the definition of parameter χ: class $1 \chi = 0$ (e.g., Alonso et al. 1990) net stresses formulation; class $2 \chi = \chi(s)$ depending on suction (s) but not of the amount of the water in the soil (V_w) (e.g., Khalili et al. 2004); class $3 \chi = \chi(V_w, s)$ (e.g., Jommi 2000) depending on suction and the amount of water in the soil. The class 3 model is adopted because of its conceptual advantages as the straightforward transition between saturated and unsaturated states and the direct incorporation of the hydraulic hysteresis.

The parameter χ, in the class 3 model, is related to the degree of saturation, different kind of expression has been recently proposed: $\chi = (S_r - S_{rres})/(S_{rsat} - S_{rres})$ (e.g., Lu et al. 2010); $\chi = (S_r - S_{r\_micro})/(S_{rsat} - S_{r\_micro})$, $\chi = (S_r)^{\alpha}$, where S_{r_micro} is the microscopic degree of sauration and α is a material parameter (e.g., Alonso et al. 2010). As a simplification, the parameter χ is considered equal to the degree of saturation S_r, because the contribution of term $S_r s$ give error prediction for high value of suction ($\geq$1 MPa) typical of clayey soils, however in this work the attention is focused on the behaviour of a silty sand. Any different expression for $\chi = \chi(S_r)$, can be easily adopted in the simple model proposed.

Many authors have already proposed the NCL equations of unsaturated soils that are dependent on the variation of S_r, such as Al-Badran and Schanz (2010), Zhang and Ikariya (2011), and Kikumoto et al. (2011). The models previously

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mentioned relate the shift of the NCL to the parameter introduced ad hoc in the formulation, while the shift proposed in this paper is derived consistently from the variation of the preconsolidation pressure with the degree of saturation.

From an engineering perspective, the objective is to provide a simple way to predict the deformation induced by wetting as a result of rainfall, for example, infiltration known as the NCL in saturated condition, the slope of the unloading–reloading line, the degree of saturation, and one additional parameter.

Material and test procedures

The soil is a low-plasticity silty sand from a steep slope in Rüdlingen, in northeast Switzerland, where a triggering experiment was carried out in March 2009 (Springman et al. 2009; Casini et al. 2010; Askarinejad et al. 2012).

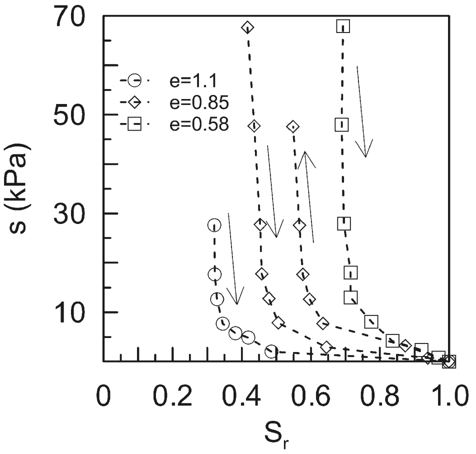
The samples were statically compacted at the target water content and void ratio. Loose soil was initially mixed to a target water content. By assuming that the water content of the wet mixture was equal to the target value, an appropriate mass of soil was compacted in one layer by one-dimensional static compression to achieve the target dry unit weight.

The water retention curve (WRC) was obtained using a Fredlund apparatus (Perez Garcia et al. 2008) under suction-controlled conditions for three statically compacted (diameter, $D = 6.3$ cm; height, $H = 2$ cm) samples with an initial void ratio e_0 of 0.58, 0.85,and 1.1, respectively, and initial gravimetric water content $w_0 = 15\%$. The results of the wetting path are reported in Fig. 1 in terms of degree of saturation $S_r = V_w/V_v$, where V_w and V_v are the volume of water and voids, respectively, and suction $s = u_a - u_w$, where u_a and u_w are the pore air and water pressures, respectively. The results show that, as the void ratio decreases, the water retained by the soil increases. For a suction $s = 10$ kPa, S_r ranges between 0.35, 0.50, and 0.75 as the void ratio decreases from 1.10 to 0.58.

The oedometer samples (7 cm in diameter) were compacted in one layer to a height of 2 cm. Four oedometer tests were performed up to $\sigma_v = 400$ kPa on compacted samples prepared with $w = 14.3\%–23\%$ also including unloading–reloading path for $\sigma_v = 200$ kPa as shown in Fig. 2*a* in terms of vertical stress, σ_v, and void ratio, e. Two samples were tested at initial constant water contents $w_0 = 14.3\%–23\%$, respectively, the others two samples were saturated and then tested (Habegger et al. 2011). As highlighted by the experimental data (Fig. 2*a*), the mechanical behaviour of the unsaturated samples can be regarded as a combination of the behaviour of the corresponding saturated soil and the structural effects induced by partial saturation. As the soil is loaded, the initial bonds due to the partial saturation are progressively damaged and the degree of saturation increases correspondingly with volume loss, while the behaviour of the unsaturated soils tends toward that of the saturated soil. The unloading–reloading paths are not affected by S_r.

Six oedometer samples, compacted at a target water contents $w = 15\%$ and 20%, respectively, were compressed up to a vertical stress σ_v of 100, 200, and 400 kPa. Then the samples at constant vertical stress were fully soaked. The vertical line in Figs. 2*b*–2*c* indicates the stress at which the samples were flooded and the change in void ratio induced by wetting in the plane e–log σ_v. For the same vertical stress, the position of the experimental points after saturation are similar to that of the samples saturated at the beginning of the test.

Fig. 1. Water retention data on reconstituted samples of Rüdlingen silty sand at three different void ratios under $\sigma_v - u_a = 5$ kPa.



Modelling framework

Many constitutive models have been developed to describe the mechanical behaviour of unsaturated soils (e.g., Wheeler and Sivakumar 1995; Romero and Jommi 2008; Sheng et al. 2008; D'Onza et al. 2011; Zhang and Ikariya 2011). Suction was recognised early as the fundamental variable in the description of the unsaturated soil behaviour. However, a second variable is generally required to represent the stabilizing influence of suction on interparticle forces and the volumetric effects of its removal or weakening, by wetting (Gens et al. 2006).

The constitutive relationships for the mechanical behaviour are defined here in terms of Bishop's (Bishop 1959) stress $\sigma'_{ij} = \sigma_{ij} - u_a\delta_{ij} + \chi(u_a - u_w)\delta_{ij}$ and suction $s = u_a - u_w$, where σ_{ij} is the total stress, χ is a weighting parameter, taking into account S_r, and δ_{ij} is the Kronecker delta.

The vertical soil skeleton (effective) stress is defined as

$$[1] \qquad \sigma'_v = \sigma_v - u_a + \chi(u_a - u_w)$$

In this work the evolution of the preconsolidation vertical stress σ'_{vc} in unsaturated conditions is defined as the product of a term that is the function of the volumetric plastic strain (σ'_{vcsat}) and a term depending on χ. Following Tamagnini (2004) the expression

$$[2] \qquad \sigma'_{vc} = \sigma'_{vcsat}\exp^{\overline{a}(1-\chi)}$$

$\overline{a}$ is adopted as a model parameter.

The change in preconsolidation effective stress is a combination of a reversible component related to change in χ and an irreversible component dependent on the development of plastic strains. The model predicts that a drying process induces some *bonding* (positive hardening) while a wetting process induces some *debonding* (negative hardening).

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Fig. 2. Oedometer compression curves on reconstituted samples of Rüdlingen silty sand: (*a*) saturated and unsaturated samples up to 400 kPa; (*b*) $w_0 = 15\%$, and (*c*) $w_0 = 20\%$ and then saturated at $\sigma_v = 100$, 200, and 400 kPa.

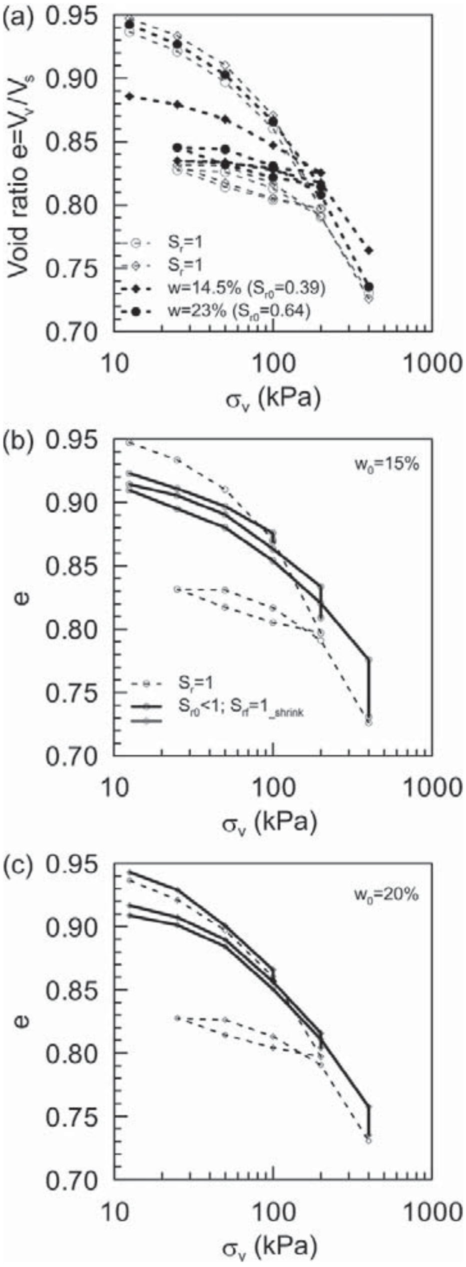


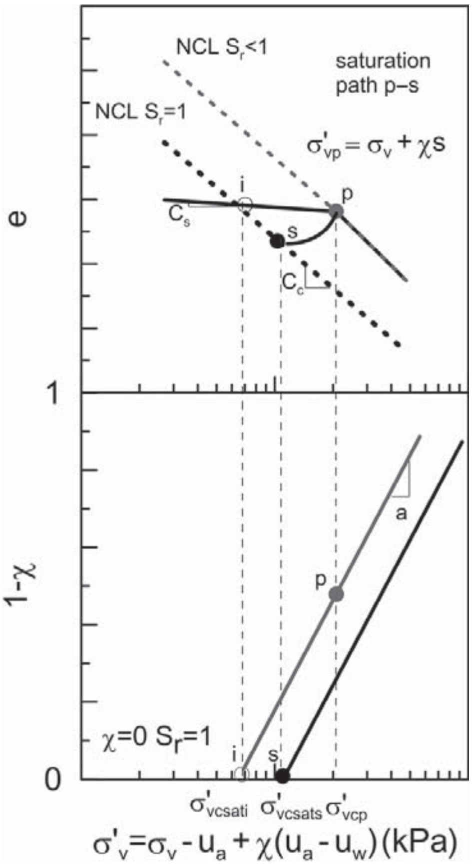
Table 1. Mechanical model parameters.

B	C_c	C_s	a
1.3	0.22	0.05	0.3

Considering an oedometric compression test starting from a virgin state, in an analogy with saturated soils, the NCL is given by

$$[3] \qquad e = B(\chi) - C_c \log\sigma'_v$$

Fig. 3. Stress path followed by a point p to saturation s. Point i represents the saturated preconsolidation vertical stress of point p. Δe_{sat} is the variation of void ratio induced by saturation predicted by the model.



where σ'_v is the vertical effective stress defined by eq. [1], $B(\chi)$ is the void ratio at 1 kPa, and C_c is the compression index. The elastic change of void ratio Δe^e by

$$[4] \qquad \Delta e^e = -C_s \log\sigma'_{vf}/\log\sigma'_{v0}$$

where C_s is the elastic swelling index and σ'_{v0} and σ'_{vf} are the initial and final value of the vertical soil skeleton stress, respectively. The parameters for the mechanical model are reported in Table 1.

The dependency of $B(\chi)$ can be obtained easily from eq. [3] and from

$$[5] \qquad e_i = B - C_c \log\sigma'_{vcsat}, \qquad e_i = e_p - C_s \log\frac{\sigma'_{vcsat}}{\sigma'_{vc}}$$

where e_i and e_p are the void ratios in saturated and unsaturated conditions, respectively, on NCL (Fig. 3), B is the void ratio at a vertical stress $\sigma'_v = 1$ kPa under saturated conditions and by substitution

$$[6] \qquad B(\chi) = B + (C_c - C_s)a(1 - \chi)$$

where $a = \overline{a}/\ln(10)$.

A decrease of parameter χ induces a shift of the NCL, parallel to the saturated one according to eq. [3] (with $B(\chi)$ from eq. [6]). During a compression phase at constant gravimetric water content the void ratio decreases inducing an increase of

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Fig. 4. Comparison between laboratory data versus the model: (*a*) water retention curves at three different initial void ratios, (*b*) compression lines in saturated and unsaturated conditions.

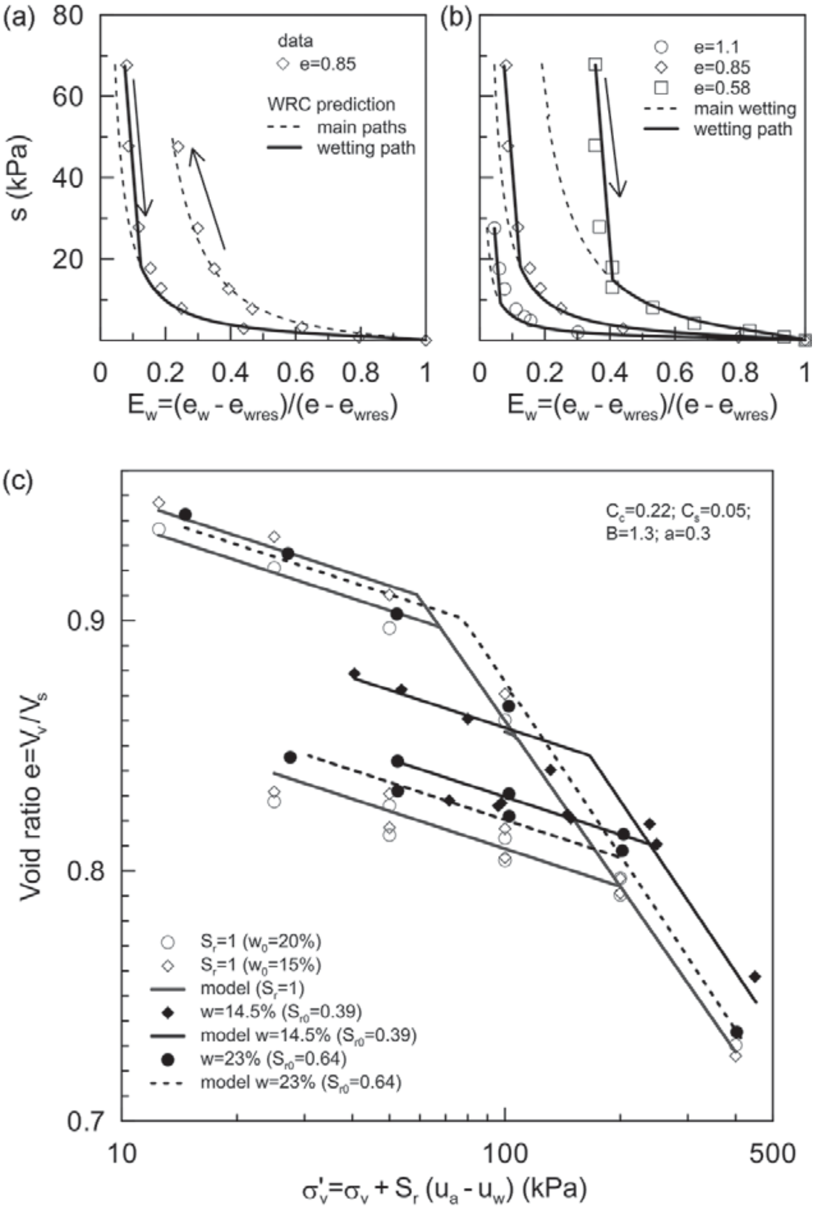

Table 2. Hydraulic model parameters.

n_0	P_0 (kPa)	b	λ_0	c
0.524	0.70	9	0.55	–2.5

parameter χ shifting the NCL, which will approach the saturated ones as χ tends to the unity.

Similar approaches are already proposed by e.g. Al-Badran and Schanz (2010), Zhang and Ikariya (2011), Kukimoto et al. (2011), and recently summarized by Sheng (2011).

The equations proposed by the aforementioned models introduce an additional parameter to capture well the experimental results, while the simple equation proposed here is derived once defined by the yielding law (eq. [2]) and the saturated parameters C_c, C_s, B (eq. [6]).

The constitutive relationship describing the water storage mechanism is defined in terms of a dimensionless water ratio $E_w = E_w(s,n)$, using a modified Van Genuchten equation (Van Genuchten 1980) as follows:

$$[7] \quad \begin{aligned} & E_w = \frac{e_w - e_{wres}}{e - e_{wres}} = \left\{1 + \left[s/P(n)^{1/[1-\lambda(n)]}\right]\right\}^{-\lambda(n)}; \\ & P(n) = P_0 e^{b(n_0 - n)}; \quad \lambda(n) = \lambda_0 e^{c(n_0 - n)} \\ & \dot{E}_w = -k_s \dot{s} \end{aligned}$$

where e_w is the water ratio defined as $e_w = V_w/V_s = S_r e$, V_s is the volume of solids, $e_{wres} = 0.30$ is the residual water ratio, P and λ are soil parameters, depending on porosity n via parameters b and c, k_s is the slope of the scanning curves here assumed linear for simplicity. The parameters obtained by interpreting the WRC are reported in Table 2.

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Comparison between the prediction and the laboratory results for the WRC is shown in Figs. 4*a* and 4*b*. In the range of suction investigated, the model fits the experimental results well over the variation with the void ratio. Figure 4*c* reports the results of oedometer tests in the plane $e - \log \sigma'_v$, where $\sigma'_v = \sigma_v + S_r s$, the suction is obtained by inverting the WRC taking into account the hysteresis of water retention curve (eq. [7]) from a known $w = w_0$ (%) and the evolution of the void ratio e during the tests.

The calibration of the parameters obtained by interpreting the oedometric results assuming the parameter $\chi = S_r$ are also reported in Fig. 4*c*. The NCL, calibrated on the experimental data, shows a rate of structural degradation tending to the saturated NCL as both the stresses and the degree of saturation increase, which reproduces the experimental behaviour well.

Model prediction

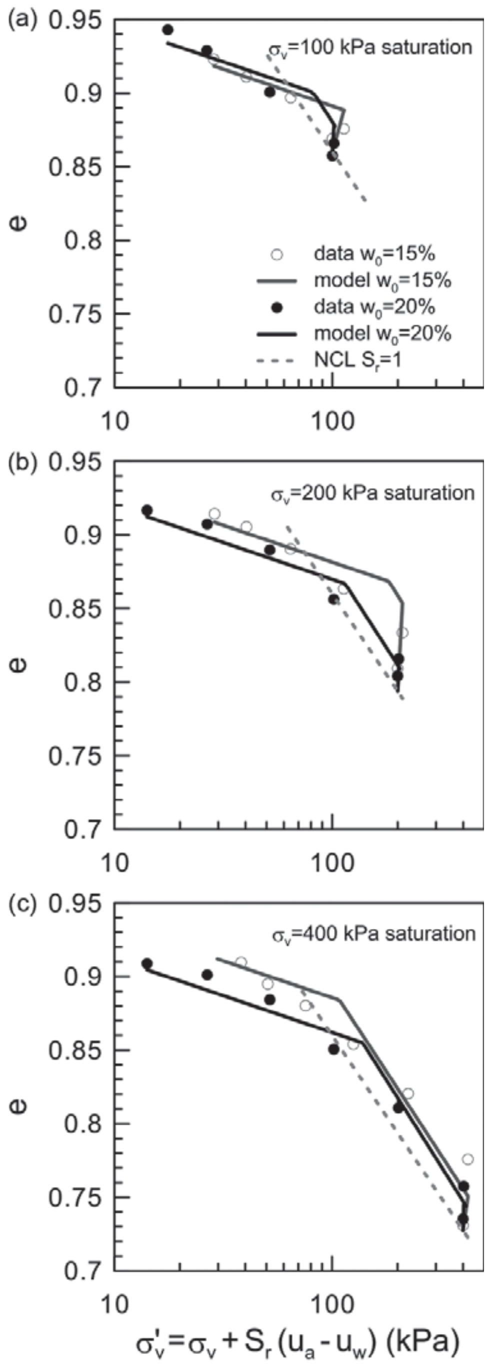
Considering complete saturation of a soil element from an unsaturated state described by p, e, S_r, s, σ_v and hence $\sigma'_{vp} = \sigma_v + S_r s$ (Fig. 3), the deformations are calculated from

$$\begin{aligned} &\Delta\varepsilon_e = \frac{C_s}{1+e_0} \log\left(\frac{\sigma'_{vcsats}}{\sigma'_{vp}}\right) \\ [8] \quad &\Delta\varepsilon_p = \frac{(C_c - C_s)}{1+e_0} \log\left(\frac{\sigma'_{vcsats}}{\sigma'_{vcsati}}\right) \\ &\Delta\varepsilon = \Delta\varepsilon_e + \Delta\varepsilon_p \end{aligned}$$

where σ'_{vcsati} is the equivalent initial saturated preconsolidation vertical stress and σ'_{vcsats} is the saturated preconsolidation vertical stress after saturation and e_0 the initial void ratio (Fig. 3).

The wetting tests performed in oedometric condition under different vertical load ranging between 100–400 kPa. The experimental results are compared with the model prediction in Fig. 5.

Fig. 5. Model predictions versus experimental data for one-dimensional compression at w_0 = 15%–20% for different vertical stress at saturation: (*a*) σ_{vsat} = 100 kPa; (*b*) σ_{vsat} = 200 kPa; (*c*) σ_{vsat} = 400 kPa.



Points to the right of the saturated NCL will shrink (collapse) during saturation, while those to the left will swell. It is obvious that the NCLs under unsaturated conditions (eq. [4]) cannot be parallel during compression because the degree of saturation increases and will converge slightly over this range of vertical stresses towards the saturated NCL in the same way as NCLs for natural soils versus reconstituted ones (e.g., Callisto Rampello 2004), which is confirmed by the oedometer test data. The degradation induced by the applied loads is quite well described by the change in degree of saturation and its influence on NCL for this type of soil. The model predicts an overconsolidated state for the point at σ_v = 100 kPa with w_0 = 15% and a normal consolidated state for the same stress with w_0 = 20% before the saturation (Fig. 5*a*), both of them shrink during saturation and the final points are quite well predicted by the model. While for the stresses σ_v = 200–400 kPa the model predicts a normal consolidated state with w_0 = 15%–20%, respectively (Fig. 5 *b*–*c*) before the saturation followed by shrinking during the flooding step. The model predicts quite well the variation of void ratio induced by soaking for samples with w = 20% and σ_v = 200–400 kPa, respectively, and for sample with w = 15% with σ_v = 100 kPa. For the other tests, the model over estimates the variation of void ratio induced by wetting.

Conclusions

The paper presents a simple model for predicting the deformation induced by wetting of an unsaturated soil (e.g., Rüdlingen silty sand). The preconsolidation vertical stress, predicted by the model, depends on the degree of saturation

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via an exponential law. The dependency of the WRC on the state of the soil was modelled with a modified Van Genuchten equation where fitting parameters depend on porosity and are obtained by interpreting the experimental results at different void ratios. The model predicts the amount of water retained by the soil at different void ratios rather well. The NCL under unsaturated conditions is described by a simple expression that which needs only one more parameter than the saturated NCL and the parameter χ.

The capability of the model to reproduce the behaviour of an unsaturated silty sand has been proved by comparing the experimental results and predictions. The proposed model, despite the simplicity, is able to reproduce the compression induced by saturation at different vertical stress and water content quite well. The model can be used with different definition of the χ parameter proposed in literature as the effective degree of saturation elevated to an exponent giving satisfactory predictions also for clayey soils.

This model can be useful for several engineering applications, such as predicting settlement of shallow foundations induced by loading and wetting.

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