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Cone penetration testing in partially saturated clayey soils: a numerical approach

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ABSTRACT: Cone penetration tests (CPTu) are frequently performed in unsaturated soils. In such conditions, the presence of suction can significantly influence the measured response, with cone tip resistance in some cases increasing by a factor of six compared to what would be observed in fully saturated conditions. Results interpreted without accounting for partial saturation may thus be dangerously misleading. Despite its practical importance, the effect of partial saturation on CPTu measurements remains poorly understood. This study employs a numerical approach to investigate cone penetration in unsaturated soils. The simulations focus on loose, low-plasticity clayey soils and examine a range of suction levels and intrinsic permeabilities to understand the effect of suction hardening and water retention properties on CPTu measurements. Special emphasis is placed on normalized cone metrics.

KEYWORDS: PFEM, numerical modelling, cone penetration testing, partially saturated soils.

1 INTRODUCTION

Cone penetration testing is one of the most important in-situ testing method for site characterization in geotechnical engineering due to its ability to provide continuous, repeatable and reliable data. A large number of interpretation techniques have been proposed, virtually enabling to estimate almost any soil parameter from this in-situ test. However, these interpretation techniques have been predominantly designed for saturated soils. Consequently, guidance on interpreting the test results in partially saturated soils remains limited.

When compared to the saturated case, the constitutive response of unsaturated soils is far more complex: suction induces an increased preconsolidation stress and tensile strength, volumetric strains develop during constant water content loading, the material may swell or collapse during wetting, permeability is heavily dependent on the degree of saturation, and the mechanical and hydraulic response are two-way coupled. For saturated soils, the constitutive model can be formulated in terms of the effective stress and the state of the soil described, for monotonic loading, by stress and void ratio. In unsaturated soils, however, two independent stress variables are typically required to formulate the constitutive model (Gens et al. 2006); and, for the same loading conditions, at least an additional variable (suction, water content or degree of saturation) is required to describe the state of the soil.

All this complexity is also transferred to the cone response. In fully saturated soils, cone resistance is primarily governed by the effective stress level and void ratio (Schmertmann 1976; Jamiolkowski et al. 2003). However, an additional variable is necessary to describe the cone response in partially saturated soils. Repeated CPTu tests conducted at the same site across different times of the year have demonstrated a clear seasonal dependence of the measured response. During the wet season, both the cone resistance and friction sleeve resistance tend to be significantly lower, whereas in the dry season, these values can increase by as much as a factor of six (see, for instance, Jommi et al. 2024).

Insights into the effects of partial saturation on CPTu response can be gained through field testing (e.g. Jommi et al. 2024) or calibration chamber experiments (e.g. Russell et al. 2024), both of which provide valuable data under natural or controlled conditions. However, these approaches are often expensive and time-consuming. In the case of field tests, capturing seasonal variations in suction and saturation typically requires repeated testing over the course of a full year, while calibration chamber tests involve complex equipment, and long consolidation times, especially if the tested material has a low permeability. As a result, numerical simulation emerges as a viable and flexible alternative.

Using numerical simulation, Monforte et al. (2025) carried out a systematic study of the effect of partially saturated conditions on cone response for loose unsaturated material. A parametric analysis examined not only the effect of initial suction and drainage conditions on cone responses, but also the effect of water retention and suction-hardening properties. Building on that set of simulations, the present study explores how partial saturation conditions govern the behavior of normalized cone metrics, build to generalize those often used in saturated soils to create CPTu-based soil classification schemes or correlate with soil properties.

2 METHODOLOGY

The numerical simulations of cone penetration testing in unsaturated soils have been performed using the Geotechnical Particle Finite Element method (GPFEM) (Carbonell et al. 2022), that has been specifically designed to simulate the insertion of structures into soil masses. The method is based on the Particle Finite Element method (PFEM) (Oñate et al. 2004). As such, the finite element method is used to compute the solution, using a Lagrangian formulation and employing low order (linear) triangular elements. This type of element facilitates the constant remeshing of the finite element discretization. Additionally, *h*-adaptive mesh refinement techniques are employed, whereby new nodes and elements are inserted within the active plastic zones to enhance the resolution and accuracy of the numerical solution.

The problem is governed by the coupled hydromechanical equations that describe the behavior of partially saturated porous media. The following simplifications are made: (i) all dynamic effects are neglected (quasi-static conditions), (ii) the gas phase remains at atmospheric pressure (this is equivalent to assuming an infinite gas permeability), (iii) there is no transfer of mass between phases and (iv) both solid and water compressibility are considered negligible.

The stiffness of the piezocone is several orders of magnitude larger than that of the soil. Therefore, the cone is considered rigid. The contact constraints between the cone and the soil are introduced into the solution using a penalty approach. The tangential part of contact is modelled using an elasto-plastic analogy and the strength of the interface is described with a generalized Coulomb law: the maximum allowable tangential stress is a fraction of the normal Bishop's stress.

The constitutive response of the soil is formulated in terms of two independent stress variables (Gens et al. 2006): Bishop's stress and suction. The reference model for the saturated material is CASM, a critical state, state parameter dependent constitutive model (Yu 1998). The yield surface of the model reads:

$$f = \left(\frac{q}{Mp^*}\right)^n + \frac{1}{\ln r}\ln\left(\frac{p^*}{p_c}\right) \quad (1)$$

where p^* is Bishop's mean stress, q stands for the deviatoric stress, M is the critical state stress ratio (which varies with the Lode angle), p_c is the apparent preconsolidation, and n and r are two parameters of the model.

The model is extended to partially saturated conditions using the Barcelona Basic Model (BBM) (Alonso et al. 1990) loading collapse curve. This way, the saturated preconsolidation stress, p_c^{sat}, and suction are related to the apparent preconsolidation stress, p_c, as:

$$p_c = p_r\left(\frac{p_c^{sat}}{p_r}\right)^{\frac{\lambda-\kappa}{\lambda_s-\kappa}} \quad (2)$$

where, κ is the swelling slope and p_r is a reference pressure and λ and λ_s are the slope of the virgin isotropic compression line under saturated and unsaturated conditions, respectively. The parameters λ and λ_s are related through a closed-form expression, with λ_s decreasing with suction (Alonso et al. 1990).

In the compression plane (void ratio – logarithm of the Bishop's stress), the isotropic compression line and critical state line are described in CASM by parallel, straight lines. Suction has the effect of moving upwards and decreasing the slope of these lines, at a rate given by the loading collapse (LC) curve.

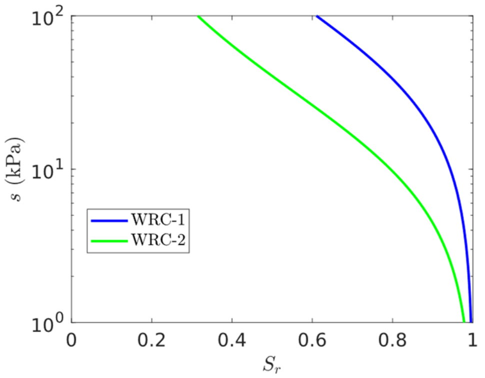


Figure 1. Adopted water retention curves.

The hydraulic model is uncoupled from the mechanical response with water retention described by a van Genuchten curve. Permeability explicitly depends on the degree of saturation, decreasing as degree of saturation reduces.

In the simulations presented below, a standard cone is pushed into the soil at a velocity of 2 cm/s. The computational domain is sufficiently large to ensure that boundary effects do not influence the results. Standard boundary conditions are applied throughout the model. In all cases, the in-situ stress state is characterized by a net vertical stress of 100 kPa and a net horizontal stress is 50 kPa.

3 MATERIAL CHARACTERIZATION

The simulation results presented below employ a set of constitutive parameters representative of a loose, fine-grained soil with low plasticity. The critical state stress ratio is $M =$ 0.98 (triaxial compression conditions). Other parameters of CASM yield surface are chosen so that the yield surface has a similar shape to the Modified Cam Clay model one. The elastic behavior is also similar to that of the Modified Cam Clay model, with parameters: $\kappa = 0.05$ and $\nu = 0.25$. In the compression plane the saturated critical state line has a slope of $\lambda = 0.15$ and a void ratio $e_0 = 1.0$ at a mean effective stress of 50 kPa.

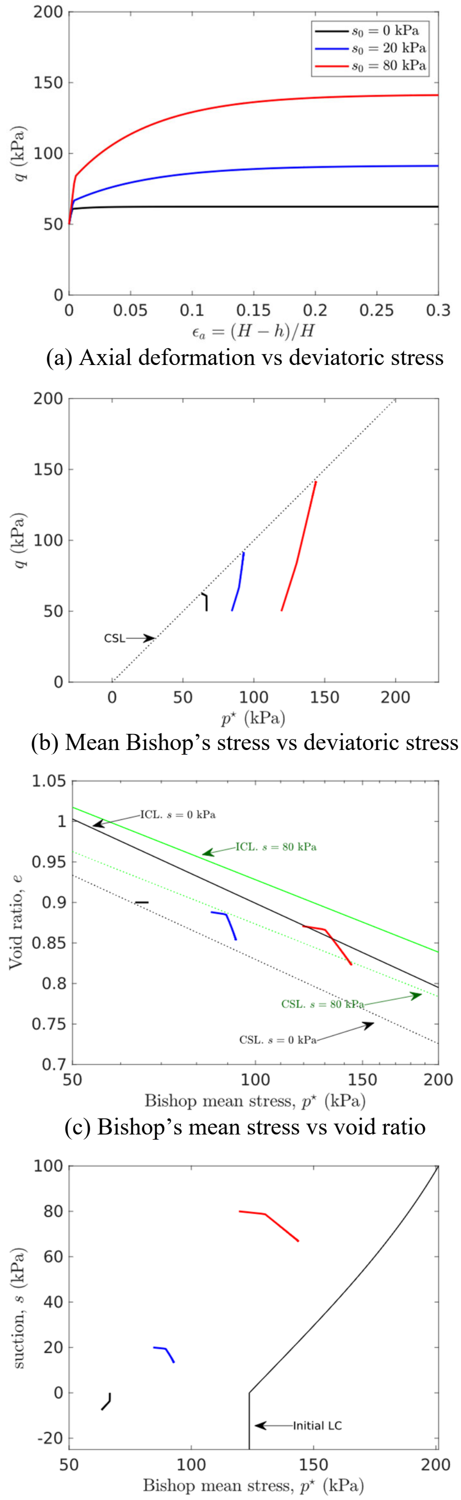


Figure 2. Material characterization in constant water content triaxial testing.

The loading collapse curve employed is reported in Figure 2 (d). Two different water retention curves (Figure 1) are employed. In this work we consider only two extreme values of saturated permeability: $k = 10^{-9}$ m/s and $k = 10^{-2}$ m/s. The smaller value guarantees constant water conditions and the larger one drained conditions. For a more complete parametric study see Monforte et al. (2025).

The material response for the case of constant water content is illustrated in Figure 2 with the simulation of triaxial compression tests at different initial suctions. In all cases, the material is initially at a net stress of $\sigma_{v0}^{net} = 100$ kPa and $\sigma_{h0}^{net} = 50$ kPa. The initial states of each simulation have been defined by drying a lightly overconsolidated saturated soil with a void ratio of $e = 0.9$ up to the desired value of suction. In all cases, drying takes place in the elastic regime, so all stress states plot in the same swelling line. These stress states coincide with the ones employed in the simulations of CPTu testing.

As expected, increasing the suction level leads to an increase of the shear strength (Figure 2(a)). The response illustrated in the other three planes depends on the initial water content. In constant water content situations, the product $e\,S_r$ remains constant. If the material is initially saturated, the constitutive response corresponds to that of an undrained triaxial test in a lightly over-consolidated material. For the rest of the materials compressive volumetric strains are possible as air is expelled, decreasing void ratio and, consequently, increasing the degree of saturation while suction decreases. This is further translated into a stress path in the Bishop's mean stress vs deviatoric stress plane that as initial saturation decreases further approximates the imposed total stress path. In the compression plane, all simulations tend to the critical state, but this lies in different lines corresponding to the suction present at the end of the test.

4 CONE SIMULATION RESULTS

4.1 *Effect of suction on cone responses*

Figure 3 reports some of the outputs of the simulations: the cone tip resistance, q_t, pore pressure at the u_2 position and friction sleeve resistance, f_s, in terms of the initial suction.

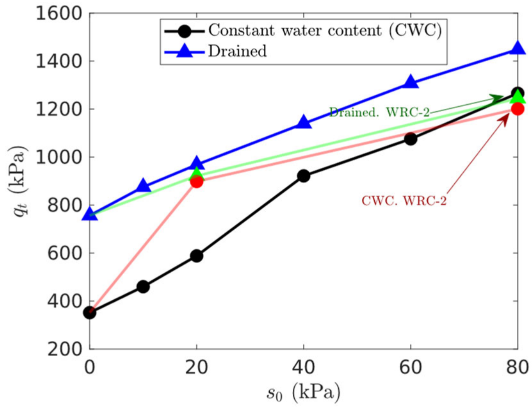
For drained conditions, the u_2 pore pressure always corresponds to the in-situ water pressure. The cone tip resistance and friction sleeve resistance monotonically increase with suction, almost doubling its value from initial saturation to $s_0 = 80$ kPa.

Under constant water content conditions, initially saturated conditions produce the largest water pressure (Figure 3). Even if the soil is initially unsaturated, the penetration of the CPT induces saturation of the soil around the tip of the cone; indeed, positive pore pressures are computed for initial suctions of 20 kPa or lower. In all cases, the recorded u_2 pore pressure is larger than the initial pore pressure.

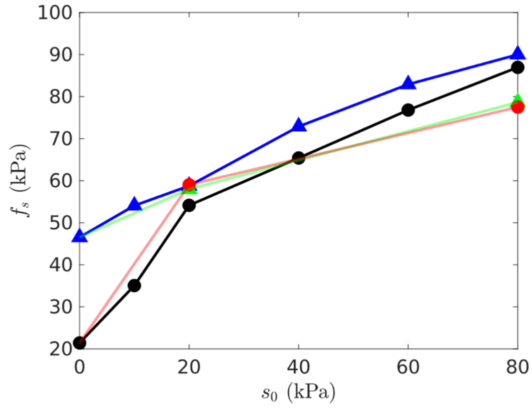
In constant water content conditions, both the cone tip and friction sleeve resistances increase by a factor of four as the initial suction increases from 0 kPa to 80 kPa. If the material is initially saturated, the cone and friction sleeve resistances for undrained conditions are almost half of those computed for drained conditions. As the initial suction increases, the dependence of cone tip and friction sleeve resistance on drainage conditions is less pronounced.

4.2 *Soil state evolution around the cone*

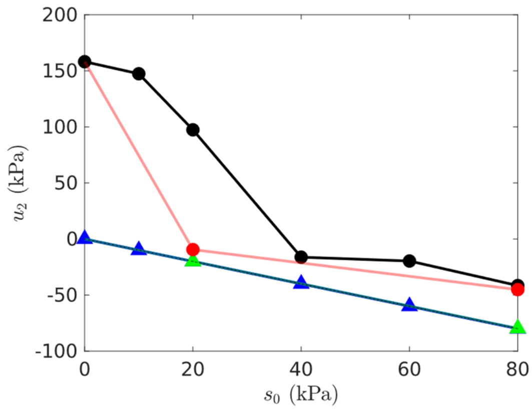
The differences observed between drained and constant water conditions and how suction influences the results can be better understood examining state evolution paths around the cone. Figure 4(a) reports the evolution of mean Bishop's stress and void ratio as the cone approaches from far field conditions until the tip passes by, observed at a point located at a horizontal distance of 2 cm from the cone axis of symmetry.



(a) Cone tip resistance



(b) Friction sleeve resistance

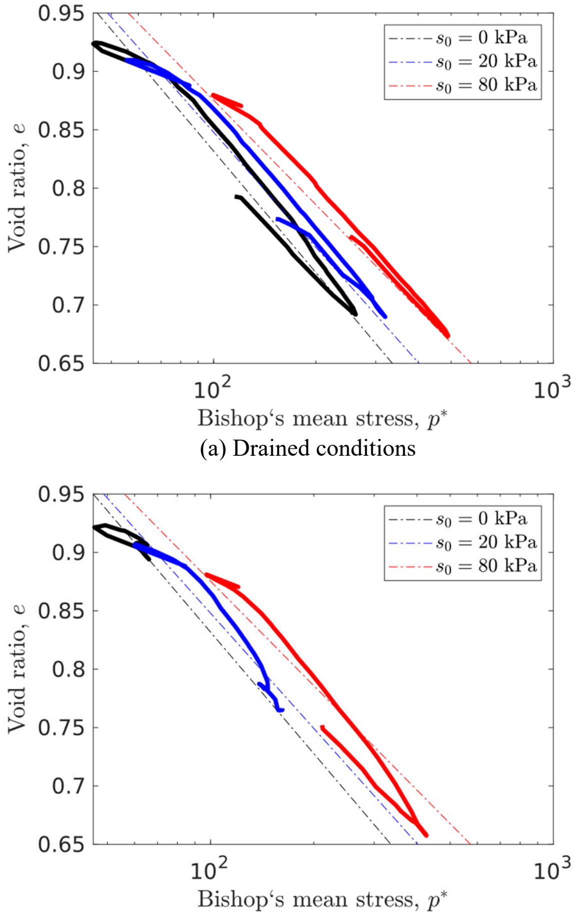


(c) u_2 pore pressure.

Figure 3. Cone metrics in terms of suction.

In drained conditions (Figure 4(a)) the initial suction level modifies both the initial state and the position of the critical state line, but it does not impact the overall response trends. As the cone approaches the observation point, Bishop's mean stress initially decreases moderately in the elastic regime, then increases sharply, first elastically and then elasto-plastically. The maximum mean Bishop's stress and minimum void ratio are observed when the tip of the cone is in front of the observation point. Afterwards, there is a reduction of the mean Bishop's stress and an increase of the void ratio in elasto-plastic regime once this observation point is in front of the shaft of the cone.

Under constant water content conditions (Figure 4(b)), the product of void ratio and degree of saturation remains constant. As for the triaxial tests presented above, the effect of this restriction is different depending on the initial water content. In contrast to the triaxial tests (the total stress path of which has a slope of 3:1), the total stress path during cone testing is affected by the initial suction.



(a) Drained conditions

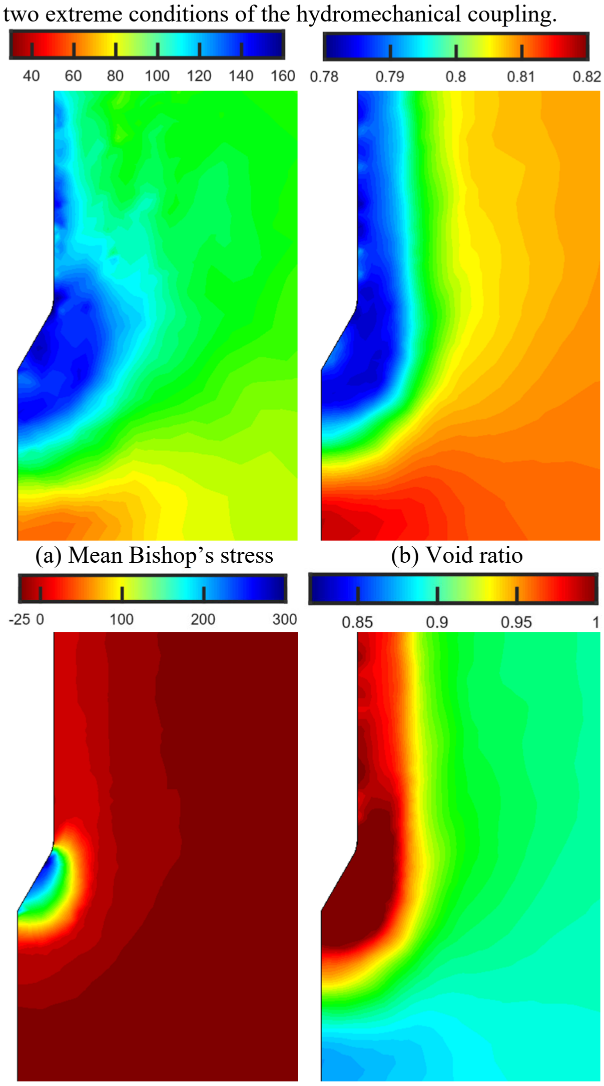
(b) Constant water content conditions

Figure 4. State evolution of a point located at a horizontal distance of 0.02 m of the axis of symmetry. Both graphs include the critical state line corresponding to the initial value of suction. WRC-1.

If the material is initially saturated, as the cone approaches this observation point, the state of the soil tends to the critical state line in undrained conditions, thus, at constant volume.

The stress path for a material with an initial suction of 20 kPa is more complex. Contour plots of the state of the soil due to cone penetration in constant water content conditions are presented in Figure 5. The cone induces a reduction of void ratio around the tip. This comes accompanied by an increase of mean Bishop's stress but also an increase of degree of saturation, which leads to the saturation of the material just in front of the tip. There, high positive pore pressures are developed. At the shaft, the soil tends to unload, thus void ratio slightly increases and the material desaturates again. Therefore, the soil beneath the tip of the cone is at critical state and fully saturated. The higher the initial suction, the lower the void ratio at which the soil reaches the saturated critical state line. As a result, the corresponding Bishop's mean effective stress and deviatoric stress at the critical state are higher (see Figure 4(b)). This, in turn, leads to an increased cone tip resistance.

In situations where the cone does not induce the saturation of the soil (for the largest initial suction), the stress path of the problem is similar for constant water content or drained conditions (Figure 4(b)). However, the cone induces a reduction of suction near the cone, which produces a downward motion and an increase of the slope of the critical state line. Therefore, the stress level around the cone is only slightly lower in constant water content with respect to drained conditions, which explains the moderate differences of cone metrics in the two extreme conditions of the hydromechanical coupling.



(a) Mean Bishop's stress (b) Void ratio

(c) Water pressure (d) Degree of saturation

Figure 5. Soil state around the cone. Initial suction $s_0 = 20$ kPa. Constant water content conditions. WRC-1.

4.3 *Normalized cone metrics*

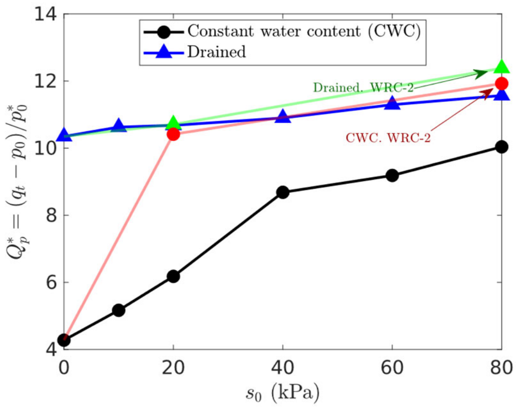
With the model employed, the impact of suction on cone tip resistance might be due to different causes, which can be defined by a reference to the saturated case:

- An increase in initial Bishop's stress, given by the product $s\,S_r$. It is well known (Schmertmann 1976; Jamiolkowski et al. 2003) that the effective stress level is one of the major controls on cone penetration resistance in saturated soils.
- Reduced stress anisotropy. Since it is assumed that the initial state of the soil is obtained by drying the soil at constant net stress, the ratio between the horizontal and vertical effective Bishop's stress (i.e. the apparent K_0) increases with suction. In saturated soils a K_0 increase raises cone tip resistance (Monforte 2018).
- Increase in plastic stiffness. As the slope of the critical state line decreases with suction, thus plastic stiffness is larger at higher suction. A larger plastic stiffness increases tip and sleeve resistance, as shown in CPTu simulations using CASM for saturated soils (Monforte et al. 2023)
- Likewise, the initial elastic stiffness also increases with suction. As the initial mean Bishop's stress is higher and κ

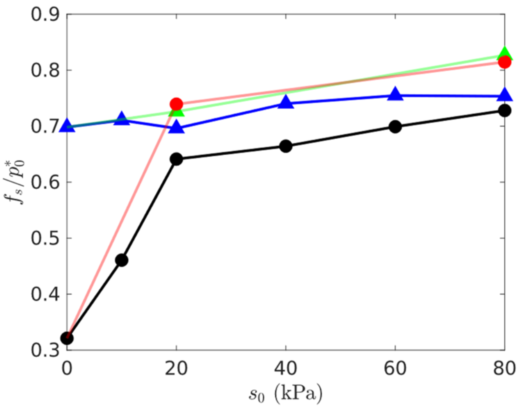
remains unchanged, the elastic bulk and shear moduli increase with suction. It is well-established that increased elastic stiffness increases tip resistance in simple elasto-plastic models (Teh & Houlsby 1991) and that effect has also been observed using CASM in saturated soils (Monforte et al. 2023).

- Initial state parameter. With this combination of constitutive parameters, drying the soil is equivalent to increasing the initial state parameter (i.e. that computed with respect to the suction-shifted critical state line, see Figure 2). For the same critical state line, the net cone tip resistance decreases as the state parameter increases (Jefferies & Been 2016).

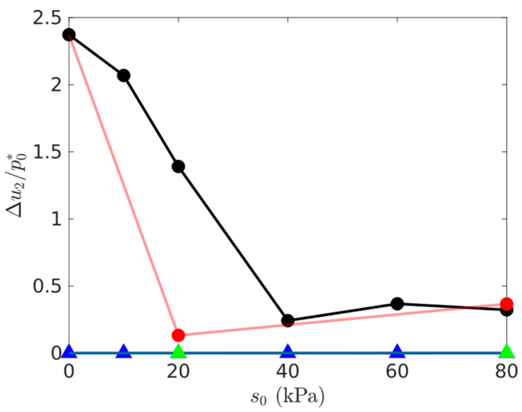
Except for the last one, all the causes listed above lead to an increase in tip resistance. It is, therefore, unsurprising that the net effect of an initial suction increase is a larger cone resistance.



(a) Normalized cone tip resistance



(b) Normalized friction sleeve resistance



(c) Normalized pore water pressure

Figure 6. Normalized cone metrics in terms of suction.

The effect of stress level and stress anisotropy can be readily separated from the others by normalizing the net cone resistance and the friction sleeve resistance using Bishop's stress. In general, CPTu measurements are normalized to facilitate test interpretation (Houlsby 1989). In saturated soils stress normalizations based either on vertical effective stress (e.g. Robertson 2016) or on mean stress (e.g. Jefferies & Been 2016) are both frequently employed. It is straightforward to generalize those normalizations to the unsaturated case using Bishop's stress and, indeed, it has been done several times (Lehane et al. 2004; Russell & Reid 2016; Tang et al. 2017; Lo Presti et al. 2018), employing different definitions of the Bishop's stress parameter χ.

Here, cone metrics are normalized using the mean stress. The generalized normalized metric for tip resistance is written as:

$$Q_t^* = \frac{q_t - p_0}{p_0^*} \tag{3}$$

where p_0 and p_0^* are the total and Bishop's mean stress. The normalized metric for pore water pressure is:

$$\frac{u_2 - u_0}{p_0^*} \tag{4}$$

where u_0 is the in-situ water pressure whereas the normalized metric for the friction sleeve resistance is:

$$\frac{f_s}{p_0^*} \tag{5}$$

Figure 6 illustrates the effect of these normalizations on the simulation results. In drained conditions, the effect of suction on the normalized measures is much smaller than the one observed in the non-normalized values of tip and sleeve resistance. The ratio of the largest to the lowest tip resistance is about 1.1, with similar values for sleeve resistance. By normalizing the results (thus, effectively removing the influence of differing initial Bishop's stress), the effect of other factors influencing cone metrics (such as the state parameter, plastic stiffness, etc…) tend to counterbalance each other. As a result, the normalized cone resistance values become largely independent of the initial suction.

Different from the drained case, large differences in the normalized metrics can be still observed for measurements at constant water content conditions (Figure 6). The normalized cone tip resistance increases by a factor larger than two, as also does the normalized friction sleeve resistance. In this case, the initially saturated case behaves as saturated, undrained material. However, for the largest initial suction, the material response is similar to that of a drained material. This results in a wider spread of normalized values than of non-normalized measures. Normalization ceases to be useful in this case.

4.4 *Parametric analysis: water retention curve*

Apart from the reference material (using WRC-1), we also consider one additional material, with less water retention capacity. The corresponding water retention curve (WRC-2) is depicted in Figure 1. This curve shares most of the parameters of the reference one and is constructed by moving downwards the curve in the $S_r - s$ plane (i.e. decreasing the air entry value).

Decreasing the air entry value has three main effects. First, for the same value of suction, the product $S_r\, s$ (which controls the stiffness and strength of the material) decreases. Second, the state parameter (with respect to both the saturated and the unsaturated critical state line) decreases. Third, the water content (for instance, the water ratio, $e_w = e\, S_r$) decreases as the water retention curve moves downwards; this way, for the same initial suction, a much larger decrease in void ratio would be required to saturate the material at constant water content conditions.

Cone metrics using the water retention curve WRC-2 are compared to those of the reference material in Figure 3. In this case, only simulations considering an initial suction of 0 kPa (naturally, rendering the same results using both water retention curves) and 20 kPa and 80 kPa are considered. In constant water content conditions and using WRC-2, the cone does not saturate the soil around the tip of the cone for the initially partially saturated cases. Still, suction reduces around the cone and the calculated values at the u_2 position are 10 kPa and 45 kPa for initial suctions of 20kPa and 80 kPa, respectively.

As the cone does not saturate the soil, the differences on the computed cone tip resistance in drained and constant water content conditions are much smaller than those observed in the reference case, except for the initially saturated case. In general, reducing the air entry value (thus, the product $s\ S_r$) is translated into a lower cone tip resistance and friction sleeve resistance.

Once results are normalized, decreasing the air entry value has the effect of increasing the normalized cone tip resistance (Figure 6). For the same suction, simulations with both water retention curves share the same unsaturated critical state line; however, the initial state (mean Bishop's stress and void ratio) of each simulation is different. Using WRC-2 produces a lower state parameter, which is translated into a higher normalized cone tip resistance.

5 CONCLUSIONS

This work has been performed to investigate the effect of partial saturation during cone penetration testing by means of numerical modelling. We have presented a series of simulations exploring the effect of the in-situ suction and drainage conditions on the cone response of a loose, clayey soil.

Both cone tip and sleeve friction resistances increase with suction, with a more pronounced increase observed under constant water content conditions compared to drained conditions. Cone metrics have been normalized using Bishop's mean stress. While normalization reduces the variability, normalized cone metrics still vary with suction. This variation is linked to changes in key soil parameters influenced by suction, such as the slope of the critical state line in the compression plane, the state parameter, or, equivalently, the apparent overconsolidation ratio -all of which are known to affect normalized cone response. Larger variations of normalized cone metrics are observed under constant water content conditions, which can be attributed to the different effect the constant water content constraint exerts on the constitutive behavior of the soil, depending on the initial water content.

6 ACKNOWLEDGEMENTS

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