

Effect of extended drying on the mechanical behaviour of a sand

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Abstract. This study investigates the influence of prolonged drying on the hydro-mechanical response of a quartz sand. Oedometer tests were performed under saturated, unsaturated, and dry conditions, on specimens prepared at different initial void ratio. The experimental results interpreted in terms of net stress, indicate that the yield stress does not exhibit a monotonic increase with suction, in contrast to the assumptions commonly adopted by elasto-plastic constitutive models for unsaturated soils. In fact, the yield stress reaches a maximum value for a given suction, followed by a continuous decrease as the samples approach the dry state. Moreover, the yield stress under dry conditions returns to value similar to that observed in the saturated state. Moreover, as expected, initial relative density plays a fundamental role in the evolution of yield stress across the entire range of investigated degree of saturation. These findings emphasize the importance of considering drying effects when assessing long-term behaviour of unsaturated granular soils.

1 Introduction

Due to exposure to intense and extraordinary climatic conditions, soils interacting with the atmosphere are subjected to continuous changes in water content. In particular, in light of rising temperatures and increasingly frequent rainfall, predicting the hydro-mechanical behaviour of such soils becomes crucial for ensuring mechanical performance, such as stiffness and strength. Specifically, prolonged drying leads, from a geomechanical perspective to a series of phenomena that significantly affect the volumetric response. Therefore, it is essential to account for potential plastic deformations when soils are exposed to significant reductions in the degree of saturation.

The behaviour of partially saturated soils, especially concerning the shear strength of unsaturated sands, has been investigated among many others by Donald (1956), Bishop & Donald (1961), and Lins & Schanz (2005) [1-3]. However, most studies in the literature focused on the influence of suction on shear strength within a relatively high saturation range, between 1 and 0.6. Experimental evidence regarding the volumetric behavior of soils at low degrees of saturation remains limited [4, 5]. Over the past decades, various elasto-plastic models have been developed to describe the mechanical behavior of unsaturated soils. These models can generally be grouped into two main categories: those based on the two independent variable approach and those relying on effective stress formulations. The first group differentiates between strains caused by changes in suction and net stress [6-11]. The second category defines an effective stress by introducing a term obtained from the product of the degree of saturation and suction

[12-16]. All these models predict a monotonic increase in yield stress with suction for a given amount of accumulated plastic volumetric strain. The resulting yield surface, commonly referred to as the Loading-Collapse (LC) curve [8], indicates that the yield stress under dry conditions reaches a maximum value that clearly exceeds the corresponding value in the saturated state.

However, the literature provides experimental evidence showing that, for high suction values, the contribution of suction to shear strength tends to reduce. For example, pioneering works by Donald [1] about the mechanical behaviour of sands show that, while shear strength initially increases with suction at high saturation degrees, it subsequently decreases when suction increases and saturation further decreases. In these conditions, the beneficial effect of partial saturation on particle contacts is lost, and the available strength returns to values close to those under saturated conditions.

To shed light on this issue, this study investigates the elasto-plastic properties of a sand across the full range of saturation—from saturated to fully dry. The evolution of yield stress with suction is presented for the same quartz sand prepared at two different relative densities, based on results from an extensive experimental campaign including conventional and suction-controlled oedometer tests.

2 Materials and methods

The tested material is a quartz sand with a grain size distribution ranging from 0.07 mm to 0.60 mm (Figure 1). Table 1 reports the physical properties of the

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material. The uniformity coefficient, calculated as $C_u = D_{60}/D_{10}$, is 1.6 classifying the material as uniform. The specific weight is equal to 26 kN/m^3 . According to the Unified Soil Classification System (USCS), the tested soil is classified as SW. The maximum and minimum void ratios were determined using a vibrating table in combination with a graduated cylindrical mold, a funnel, and a precision balance. The resulting values were: $e_{\min} = 0.47$ and $e_{\max} = 0.96$.

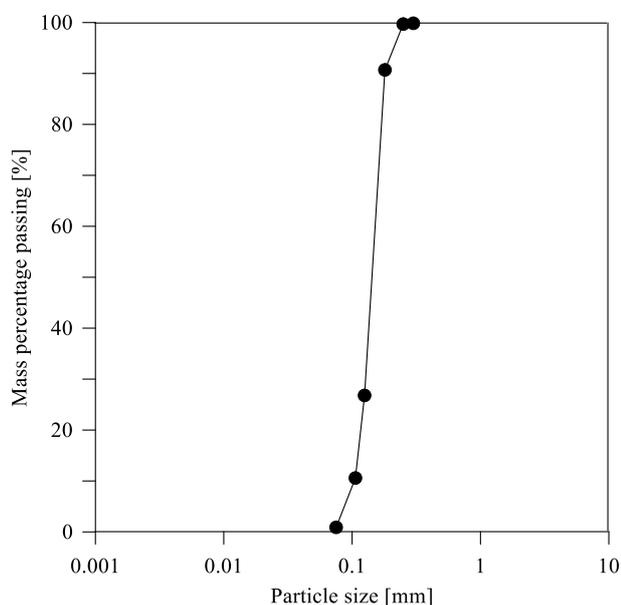


Fig. 1. Grain size distribution of quartz sand.

All specimens for the oedometer tests were prepared using the water pluviation method directly inside the oedometer ring. Table 2 reports the physical properties of the specimens used in the testing program.

To study the effect of relative density on volumetric behaviour, two different initial void ratios were selected. The first series of specimens was prepared by compacting successive layers of equal thickness directly inside the ring. The target initial void ratio was $e = 0.77 \pm 0.01$, corresponding to a relative density of $38 \pm 4\%$.

For the second series, a different technique was adopted. The sand was poured into the oedometer ring through a funnel at a constant drop height, following a circular motion. This method produced specimens with void ratios ranging from 0.85 to 0.90, approaching e_{\max} , and corresponding relative densities between 13% and 23%.

Table 2. Characteristics of the tested specimens.

e_0	Dr (%)	w_0 (%)
0.87 ± 0.02	18 ± 5	33.1 ± 0.8
0.77 ± 0.01	38 ± 4	28.9 ± 0.6

The specimens were subjected to oedometer tests in saturated and dry conditions using a standard oedometer

(diameter 56 mm, height 20 mm, maximum vertical load 6 MPa).

For unsaturated tests, a modified oedometer with a 33 mm diameter and 11 mm height was used (Figure 2). The suction-controlled oedometer allowed suction application through the negative water column method. Suction was maintained using a cellulose membrane (Pall Corporation GN-6 Metricel™) with a nominal pore diameter of $0.45 \mu\text{m}$, corresponding to a capillary breakthrough pressure of 250 kPa. This membrane was placed at the base of the specimen and connected to a graduated burette, which applies a negative pore water pressure by lowering the water level.

Table 1. Physical properties of the material.

Gs	f_{sand} (%)	D_{50} (mm)	e_{\max}	e_{\min}
2.65	100	0.16	0.96	0.47

The burette had a resolution of 0.095 cm^3 and was constantly monitored during the tests to track inflow/outflow volumes, verify suction equilibrium, and adjust the burette level when necessary.

Partially saturated oedometer tests were conducted by initially applying a total vertical stress of 30 kPa. Once suction was imposed, the specimen was loaded incrementally up to 5.4 MPa and then unloaded back to the initial 30 kPa.

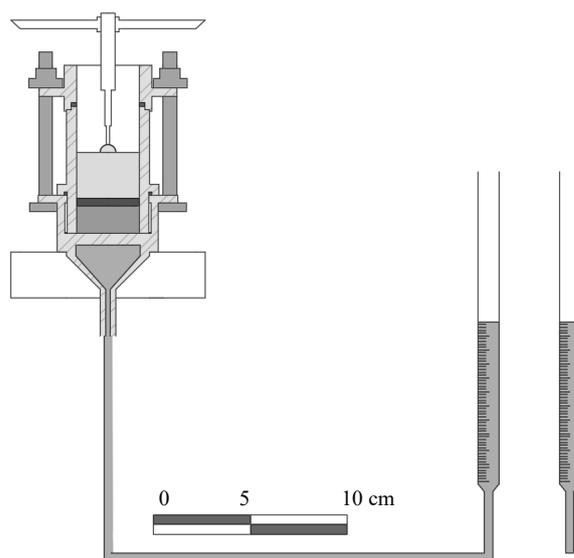


Fig. 2. Oedometer device for partially saturated soil testing, using the negative water column method for suction control. One burette is used to apply suction and monitor changes in water content, while a second burette records water volume losses due to evaporation.

The same setup, with a slightly modified procedure, was also used to determine the soil water retention curve (SWRC) by maintaining constant load and varying suction in steps. Since the sample was prepared using the

water pluviation method, the initial degree of saturation was equal to 1. The degree of saturation of the sand decreased once the suction exceeded 1.8 kPa.

Displacements were measured using an LVDT with a resolution of 1 μm . Recorded water volume changes were adjusted by subtracting evaporation losses, which were quantified using a control burette not connected to the testing system.

The tests presented in this study include a total of twelve oedometer tests six on specimens with initial void ratio $e = 0.77 \pm 0.01$, and six with initial void ratios between 0.85 and 0.90. The oedometer curves were elaborated for each test, and the yield stress was determined using a method based on the procedure proposed by Boone [17].

The main drying water retention curve is shown in Figure 3. Equalisation points corresponding to the imposed suction levels are reported for all specimens, prepared with both initial void ratios.

All experimental data were fitted using the Van Genuchten [18] equation:

$$S_r = 1 / [1 + (\alpha s)^n]^m \quad (1)$$

where α , n , and m are fitting parameters.

The fitted parameters were the following: $\alpha = 0.13 \text{ kPa}^{-1}$; $n = 3.30$ and $m = 1.71$.

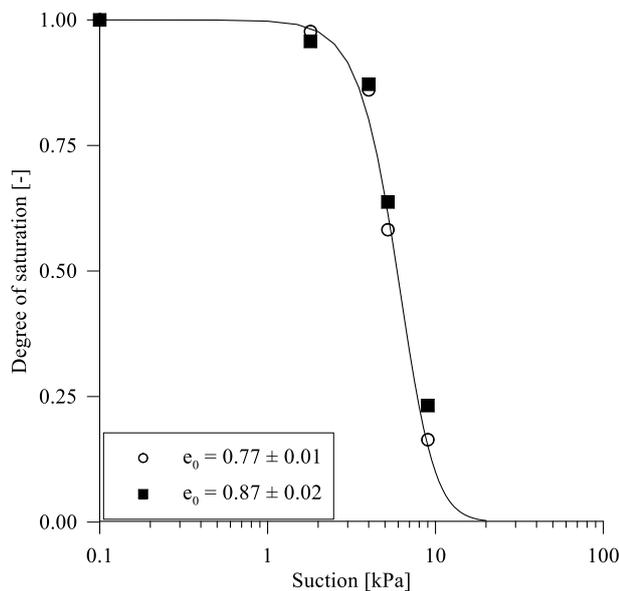


Fig. 3. Soil water retention curve - main drying.

3 Experimental results

The results of both conventional and suction-controlled oedometer tests are presented in the $\sigma_{v,\text{net}} - e$ plane in Figure 4 and 5. Specifically, Figure 4 refers to specimens prepared with an initial void ratio of 0.77 ± 0.01 . The figure includes results from two saturated tests ($s = 0$), three partially saturated tests at different suctions ($s = 1.8 \text{ kPa}$, 5.2 kPa , and 11 kPa), and one test under residual saturation conditions ($s = 16.6 \text{ kPa}$). This latter condition was obtained by allowing the sample to equilibrate with

laboratory conditions and disconnecting it from the suction-controlling burette. The associated suction value was estimated based on the water retention curve shown in Figure 2.

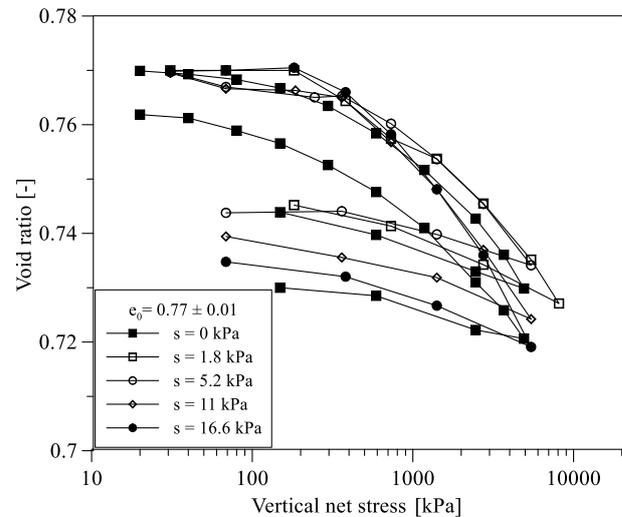


Fig. 4. Oedometer curves, presented in terms of void ratio and net vertical stress, for specimens prepared with an initial void ratio of 0.77.

Figure 5 presents the results for specimens prepared with void ratios close to e_{max} . It shows two saturated tests, three partially saturated tests ($s=1 \text{ kPa}$, 1.8 kPa , and 5.2 kPa), and one test conducted under residual saturation state ($s = 16.6 \text{ kPa}$).

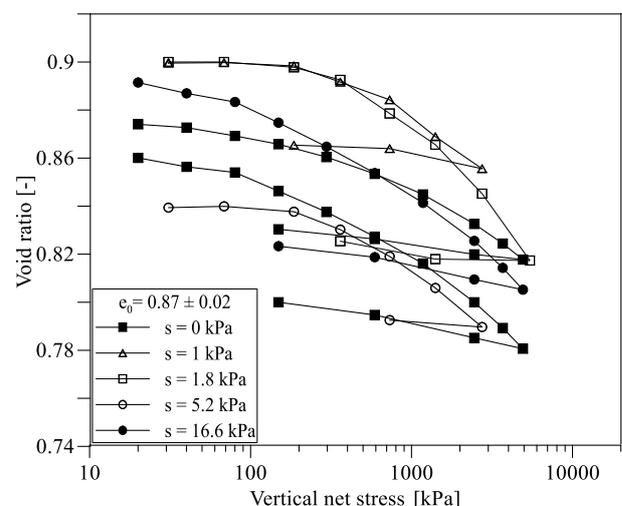


Fig. 5. Oedometer curves, presented in terms of void ratio and net vertical stress, for specimens prepared with a void ratio of 0.87 ± 0.02 .

To provide a more comprehensive overview, Figure 6 shows the evolution of yield stress as a function of suction, distinguishing between the two initial void ratio values. Figure 6 clearly shows that, in both analysed

cases, the yield stress is significantly influenced by the imposed suction value. The analysis of the results indicates that the beneficial effect of suction on yield stress is confined to a well-defined suction range, between 0 and 5.2 kPa. Relative density has a significant influence on the mechanical behaviour of the material, leading to an increase in both yield stress and stiffness. This effect is attributed to the intergranular contact stresses in denser packings, which progressively develop with increasing compaction. A denser structure limits particle rearrangement and results in smaller overall deformations.

The evolution of the yield stress is characterized by a pronounced increase for suction values corresponding to degrees of saturation between 100% ($s = 0$) and 60% ($s = 5.2$ kPa), as also indicated by the retention curve in Figure 2. Starting from a saturated state, the soil reaches a quasi-saturated condition, i.e. degree of saturation of about 90–85%, at a suction value of 1.8 kPa. In this state, the liquid phase remains continuous throughout the sample, while the air phase exists only as isolated nuclei. When the degree of saturation drops below 85%, the soil enters in a partially saturated state, characterised by the continuity of both liquid and air phases. In this condition, suction plays a beneficial role in the mechanical behaviour, as capillary menisci reinforce interparticle contact stability and, consequently, contact strength [19].

At lower degrees of saturation and higher suction levels, the air phase becomes dominant. In such conditions, most pores have emptied, and the number of capillary menisci within the soil skeleton has drastically decreased—approaching zero under residual saturation conditions. As a result, the beneficial effect of suction nearly vanishes, and the yield stress under dry conditions becomes essentially equivalent to that in saturated conditions.

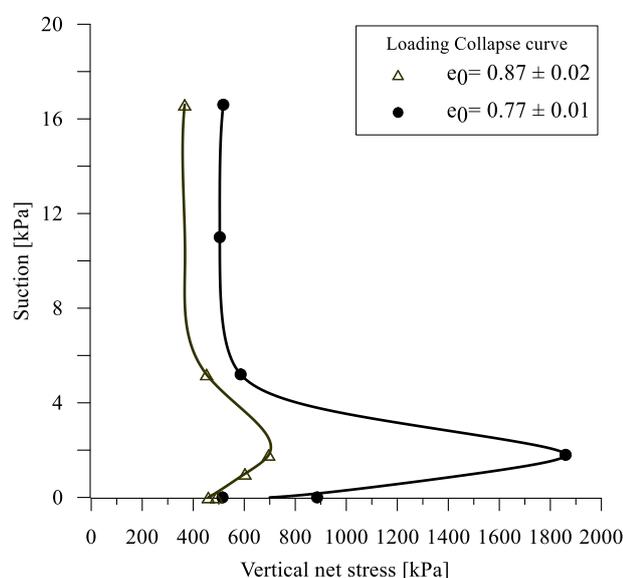


Fig. 6. Evolution of the Loading Collapse (LC) curve for different initial void ratios.

Then, LC curves exhibit a distinct non-monotonic trend with suction. Notably, the maximum yield stress occurs at an intermediate suction value between the saturated and the residual saturation states. This observation aligns with previous findings by Donald [1] regarding the shear strength behaviour of unsaturated sands.

4 Conclusions

The oedometer tests conducted in this study highlight that the yield stress—and consequently the elastic strain domain to which the soil is subjected—is strongly influenced by partial saturation conditions. The investigation of yield stress evolution with suction, performed across the full range of degrees of saturation, revealed that beyond a certain suction threshold, the yield stress tends to decrease, converging toward similar values in both saturated and dry states. Test performed on sandy samples prepared at different initial void ratio confirmed this observation, also highlighting the role of relative density in increasing the effect of suction on the measured yield stress.

The new shape of the LC curve is consistent with the principles of classical soil mechanics, which suggest that, in terms of effective stresses, the volumetric behaviour of soils under saturated and dry conditions is analogous. Moreover, the non-monotonic shape of the Loading-Collapse curve suggests that plastic deformations may occur even when drying takes place under vertical stresses between the maximum yield stress and the yield stress corresponding to the lowest explored degree of saturation.

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005 - RETURN CUP B73C22001220006)

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