Effect of Matric Suction on Monotonic and Cyclic Behaviour of a Low-Plastic Silty Soil from Sakarya Region

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Abstract. Shallow soil layers subjected to seasonal wetting and drying cycles are typically located above the groundwater table and experience negative pore water pressures. Many geotechnical problems are associated with the behaviour of these soils. Therefore, instead of relying solely on saturated soil mechanics, incorporating unsaturated soil mechanics principles provides more realistic results. In unsaturated soils, compressible air within voids leads to matric suction and net stress, two critical stress variables governing strength and deformation characteristics. The complex behaviour of unsaturated soils under static and dynamic loading continues to be a research focus. This study investigates the effect of matric suction on the monotonic and cyclic behaviour of low-plasticity silty soil from the Sakarya Basin. Laboratory tests employed a sophisticated unsaturated triaxial testing system that applies matric suction using the axis translation technique, enabling controlled monotonic and cyclic loading. Cylindrical specimens, reconstituted by using the moist tamping method to replicate in situ relative density, were consolidated under a specific net stress at three different matric suction levels before fully undrained axial loading. Throughout the tests, pore water and air pressure responses, as well as axial and volumetric deformations, were monitored. Results demonstrated that matric suction significantly influences soil behaviour. In both monotonic and cyclic tests, increasing matric suction enhanced strength and reduced pore water pressure increments. In particular, in cyclic tests, conducted at a single cyclic stress ratio, specimens with lower suction experienced large deformations and cyclic failure, whereas specimens with higher matric suction did not fail. These findings contribute to understanding the mechanical behaviour of unsaturated silty soils and provide a foundation for future research.

1 Introduction

The behaviour of near-surface soil layers is directly influenced by soil-water interactions due to seasonal wetting and drying processes. These layers, typically located above the groundwater table, are in an unsaturated state. However, in certain conditions, even when saturated, they may still be affected by negative pore water pressures (or matric suction) due to capillary forces [1, 2]. In many geotechnical engineering applications, such as slopes and compacted embankments, soil behaviour is governed by negative pore water pressures [3, 4]. Unlike saturated soils, where only incompressible water fills the voids, unsaturated soil profiles contain both water and compressible air within the pore spaces [5]. Consequently, when subjected to cyclic or monotonic loading, unsaturated soils exhibit distinct pore pressure responses and deformation characteristics [6, 7].

The effect of matric suction and net stress on the strength of unsaturated soils can essentially be considered analogous to the influence of confining pressure in saturated soils. As these effects increase, greater strength and dilatancy occur under loading [8]. In the literature, laboratory studies investigating the mechanical behaviour of unsaturated soils have generally been conducted using triaxial testing systems [6]. In these studies, soils subjected to varying matric suction and net stresses were evaluated under different conditions, and their monotonic responses were measured. Ciu and Delage [9] reported that the strength of compacted unsaturated silt increases proportionally with applied matric suction. Additionally, as matric suction increases, the soil behaviour transitions from contractive to dilative. Banerjee et al. [10] and Barahona et al. [11] obtained similar experimental results in their studies on silty sands. Kimoto et al. [12] demonstrated through drained and undrained triaxial tests on sandy soils that an increase in net stress enhances strength. Moreover, at high matric suction levels, smaller volumetric deformations were observed.

It is generally stated that loose sands in a saturated state and low-plasticity silts lose their stability and undergo cyclic failure under repeated loading. However, during the 2003 Miyagi earthquake, sandy soils exhibiting fluid-like behaviour were observed despite being unsaturated [13]. Following the 2011 Tohoku earthquake in Japan, where liquefaction was widely

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observed, researchers have increasingly focused on the cyclic behaviour of unsaturated soils to enhance their cyclic resistance. Studies examining the cyclic failure behaviour of unsaturated soils have primarily concentrated on sands [14, 15]. However, some studies have also demonstrated that silty soils, which are more challenging to characterize, can also exhibit cyclic failure [16, 17]. Okamura and Noguchi [16] investigated the cyclic failure behaviour of unsaturated non-plastic silts and found that resistance increased linearly with matric suction. Nishimura [17] studied the effect of matric suction on excess pore water pressure in silty soils subjected to repeated loading. Additionally, Tsukamoto et al. [18] examined the variation in cyclic resistance of two silty soils under unsaturated conditions using triaxial tests.

This study focuses on the influence of matric suction on monotonic and cyclic behaviour of unsaturated low-plasticity silt. For this purpose, a series of matric suction-controlled monotonic and cyclic triaxial tests were conducted on reconstituted specimens prepared using the moist tamping method. In the experiments, in addition to the saturated specimen, unsaturated specimens consolidated under varying matric suctions while maintaining constant net stress were tested. All the tests were performed with a sophisticated unsaturated triaxial apparatus used Hilf's [19] axis translation technique in University of Naples Federico II (Italy).

2 Experimental study

2.1. Material

In this study, the low-plasticity silty soil, coming from Sakarya region (north-western Turkey) was used. The physical properties of the low-plasticity Sakarya silty soil are presented in Table 1 [20]. According to ASTM D2487, it is classified as low-plasticity silt (ML). Relevant ASTM standards were followed in the physical tests. The grain-size distribution of low-plasticity silt was also given (Fig. 1).

Table 1. Physical properties of Sakarya silty soil.

Physical property	Value	Standard
Gs	2,74	ASTM D854
D_{50} (mm)	0,07	ASTM D2487
Cu (D_{60}/D_{10})	14,4	ASTM D2487
Silt (d<0,06 mm) (%)	37,6	ASTM D1140
Clay (d<0,002 mm) (%)	6,3	ASTM D1140
w_P (%)	20,9	ASTM D4318
w_L (%)	27,5	ASTM D4318
Ip (%)	6,6	ASTM D4318
k (m/s)	$1,86. 10^{-6}$	ASTM D5084
Organic content (%)	9,3	ASTM D2974

The tested soil falls within the liquefiable zone according to the approaches of Seed et al. [21] which evaluate the liquefaction potential of Sakarya fine-grained soils (from [22]) based on physical properties (Fig. 2).

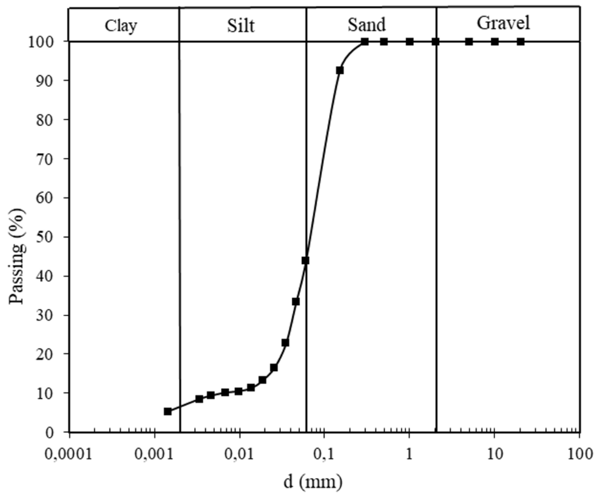

Fig 1. Grain-size distribution of silty soil.

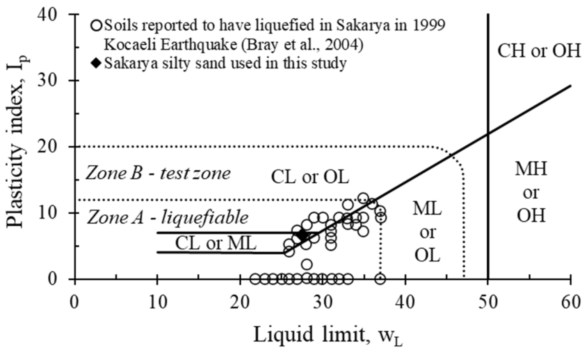

Fig 2. Liquefaction assessment of Sakarya (Adapazarı) soils (modified after [21]).

2.2 Unsaturated triaxial apparatus

In this study, a sophisticated unsaturated triaxial cell capable of matric suction control by applying air and water pressures (Unsaturated Stress Path: USPv2) was utilized (Fig. 3). This system, which applies matric suction using the axis translation technique, has the capacity to perform both monotonic and cyclic loading. The original version of the apparatus, USP, was developed at the Geotechnical Laboratory of the University of Naples Federico II by Rampino [23] through the modification of the triaxial cell initially designed by Bishop and Wesley [24]. Later, to reduce the excessively long testing durations, the USPv2, a double-walled system allowing bidirectional drainage, was introduced with contributions from Megaris Company [25].

The USPv2 precisely applies axial load, confining pressure, pore water pressure, and pore air pressure throughout the testing process. The system performs these operations based on feedback received from high-precision sensors integrated into the apparatus. Consequently, the system can dynamically respond to external influences and maintain the desired conditions throughout the test duration.

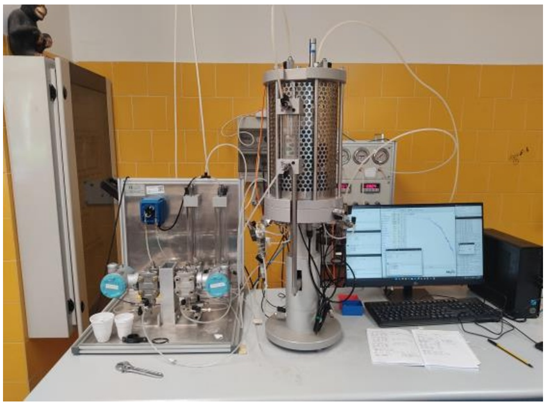

Fig 3. Double-walled unsaturated stress path (USPv2), University of Naples Federico II.

In unsaturated soils, volume change occurs during and after the consolidation process under applied matric suction and net stress, as well as during monotonic or cyclic axial loading [5]. To measure the volume change of the specimen during testing, radial volume (left) and water volume (right) sensors integrated into the system are presented in Figure 4.

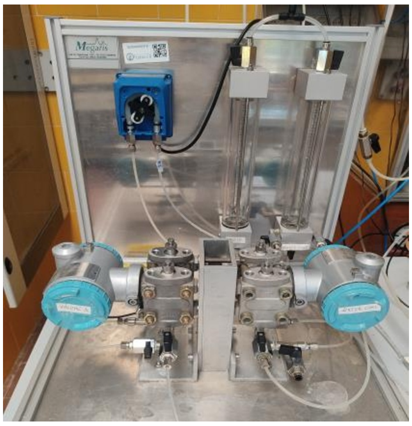

Fig 4. Total volume change and water volume transducers.

In the USPv2, the developed drainage system includes a combination of two different porous disks mounted on the base plate and top cap (Fig. 5). This combination consists of an annular porous stone connected to the pore air pressure line and a circular ceramic disk with a high air entry value (HAEV) of 5 bar connected to the pore water pressure line.

2.3 Testing program

To investigate the effect of matric suction on monotonic and cyclic behavior, three monotonic and two cyclic triaxial tests were performed under undrained conditions (both air and water). The details of the experimental program are presented in Table 2. One monotonic test (M_0_50, Table 2) was conducted in saturated conditions by using the traditional triaxial Bishop cell [24]. The cylindrical specimens used in the experiments, with a diameter of 38 mm and a height of 76 mm, were prepared using the moist tamping method. The specimens were compacted in five equal layers within a plexiglass mold of appropriate diameter and height at an initial water content of approximately 18%, achieving initial conditions of 50% saturation and 40% relative density. Specimens were saturated using the back-pressure method. Once the pore pressure coefficient, B>0.95, the specimens were consolidated under an effective stress of 50 kPa. When the water outflow (or volumetric change) stabilized, the specimens were subjected to undrained monotonic loading. The loading rate was set at 0.02%/min.

Regarding unsaturated tests, ceramic disks were saturated by applying 6 bar water pressure for 24 hours.

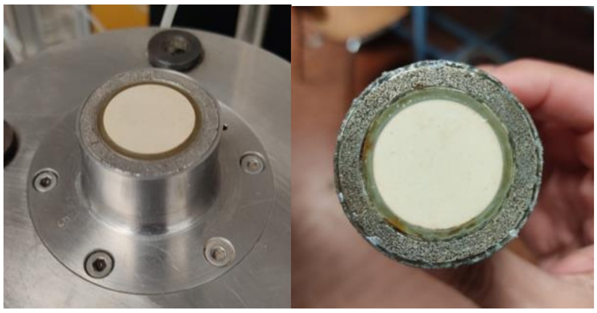

Fig 5. Porous stone and ceramic disk combination placed on base pedestal and top cap.

The experimental procedure for unsaturated tests consists of the following stages: initial matric suction measurement, matric suction equilibration under low net stress, completion of matric suction-controlled consolidation by increasing net stress, and monotonic or cyclic loading. After preparation, the cylindrical specimen (d=38 mm, h=76 mm) was placed between saturated ceramic disks.

Table 2. Triaxial monotonic and cyclic testing program.

Test	e	Sr	s (kPa)	σ_{net} (kPa)	σ' (kPa)
M_0_50	0.97	100	-	-	50
UNM_5_50	0.93	54	5	50	-
UNM_15_50	0.95	45	15	50	-
Test	**e**	**Sr**	**s (kPa)**	**σ_{net} (kPa)**	**CSR**
UNC_5_40	1.01	50	5	50	0.41
UNC_15_40	1.00	43	15	50	0.40

For the initial matric suction measurement, a net stress of 30 kPa was applied (with air valve open and without water drainage), and the resulting pore water pressure (u_w) within the specimen was recorded. The initial matric suction (u_a–u_w) was measured as approximately 2 kPa for all specimens. Subsequently, while maintaining constant net stress (confining pressure and air pressure held constant), a water pressure corresponding to either 5 kPa or 15 kPa matric suction was applied. The system was allowed to equilibrate until water outflow ceased (with both water and air drainage open). Once the specimen reached equilibrium under the applied matric suction, the net stress was increased to 50 kPa by increasing only the confining pressure. The specimen, equilibrated under the target net stress and matric suction conditions, was then subjected to axial loading.

Monotonic and cyclic loadings were performed under undrained conditions (air and water valves are closed), and pore pressure responses were monitored. In unsaturated monotonic tests, the loading rate was set at 0.02%/min. Unsaturated cyclic tests were conducted at a Cyclic Stress Ratios (CSR) of 0.40 – 0.41 and a loading frequency of 0.003 Hz, where CSR is defined as the ratio between deviatoric stress (q_{cyc}) and two times net stress (σ-u_a).

3 Experimental results

3.1 Monotonic tests

This section presents the results of the monotonic tests, the testing conditions of which are provided in Table 2. Figures 6–9 compare the test results of saturated (the matric suction value is theoretically assumed to be zero), 5 kPa and 15 kPa of matric suction specimens under an effective or net stress of 50 kPa. Figure 6 illustrates the stress-strain relationships influenced by matric suction. The specimen with a higher initial matric suction exhibited a greater deviatoric stress at the same axial strain, even though the unsaturated tests return similar results. The difference seems to exist only at higher axial strain (ε_a>5%). Saturated soil (M_0_50) exhibits a different behaviour, a peak and a strain softening at higher axial strain. In cases where the peak deviatoric stress was not reached under loading, an axial strain of approximately 18% was adopted as the failure criterion.

To plot the results in the plane p’- q, it is important to define the effective stress in both saturated and unsaturated soils. In saturated soils under stress, the stress variables consist of total stress (σ) and pore water pressure (u_w). Therefore, the effective stress (σ’) can be calculated using the Terzaghi approach ($\sigma' = \sigma - u_w$).

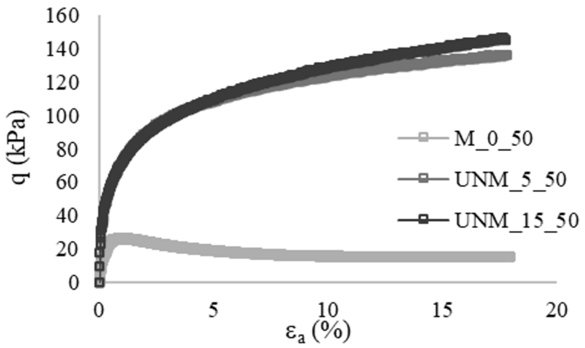

Fig 6. Stress-strain relations from monotonic tests under fully undrained conditions.

The presence of compressible air in unsaturated soils introduces an additional stress variable. Due to the increased number of stress state variables (σ, u_a, u_w) Terzaghi’s equation is no longer applicable. This complexity has led researchers to introduce modifications to the effective stress approach. Bishop [26] proposed an effective stress equation for unsaturated soils (Eq. 1).

$$\sigma' = (\sigma - u_a) + \chi (u_a - u_w) \quad (1)$$

Here, χ is a parameter dependent on the degree of saturation. In this study, χ is assumed to be equal to the degree of saturation. Figure 7 presents the stress paths in terms of deviatoric stress (q) and mean effective stress (p’). Under monotonic loading, while the mean effective stress decreased in the saturated specimen, it increased in the specimens subjected to 5 kPa and 15 kPa matric suction. So, as reported by other authors matric suction is able to change the soil behaviour from contractive (s=0 kPa) to dilative (s=5 and 15 kPa). Furthermore, the final points of the stress paths converged on a straight line with a slope of 1.46, which corresponds to a friction angle of 34,5°. In the saturated specimen, the development of pore water pressure led to a reduction in effective stress, resulting in unstable behavior. Conversely, in the unsaturated specimens, the stress paths followed a linear increasing trend.

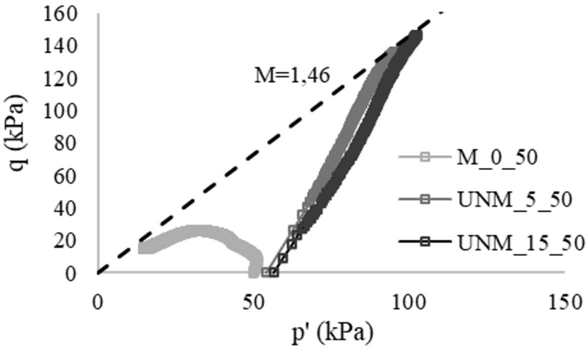

Fig 7. Stress paths under fully undrained conditions.

Figure 8 illustrates the response of pore pressures to deformation under the applied stress. The effect of matric suction is compared in the pore pressure (u_a and u_w)–axial strain (ε_a) plane. As the applied matric suction decreases or the degree of saturation increases, the incompressible water within the soil voids responds by bearing a higher proportion of the applied stress. In unsaturated specimens subjected to matric suction, the presence of a high proportion of compressible air in the voids prevented a significant increase in pore water pressure. Also, it is seen that pore air pressure responses are different. The tendencies of pore air and pore water pressures are contrary in higher matric suction. As a result, the matric suction inside the specimen increases. In lower matric suction, the pore pressures move together, and the matric suction remains almost constant.

Under the applied matric suction, the shear strength of the unsaturated specimen varies directly proportional to matric suction [5]. Fredlund et al. [27] reported that, under increasing matric suction, the apparent cohesion (c_a) of unsaturated soils increases due to the additional contribution of friction angle. Figure 9 illustrates that an increase in matric suction leads to higher cohesion values

3.2 Cyclic tests

Tsukamoto et al. [18] stated that cyclic failure is nearly impossible in silty sands with a degree of saturation (S_r) below 70%, while Okur and Umu [28] reported that sandy soils with S_r below 60% exhibit sufficient resistance to cyclic failure.

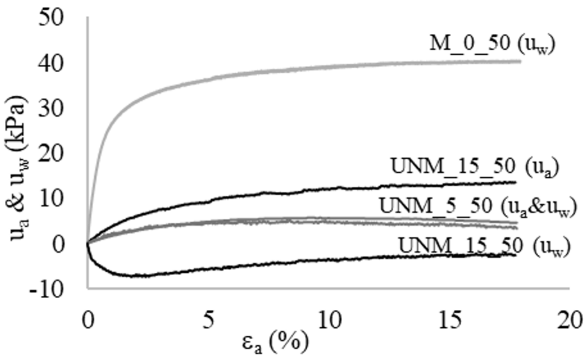

Fig 8. Pore pressure responses-axial strain relations under fully undrained conditions.

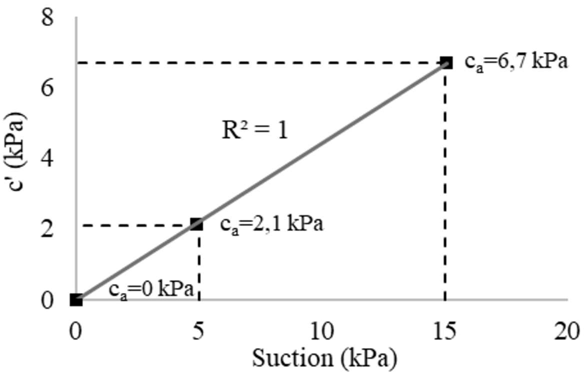

Fig 9. Change of the apparent cohesion with matric suction.

In this section cyclic tests on unsaturated soil have been presented. Figures 12–15 present the results of the cyclic tests described in Table 2. The behavioural responses of unsaturated specimens equilibrated under different matric suction conditions were evaluated at a similar cyclic stress ratio (CSR = 0.40 and 0.41). In this study, failure was defined as reaching the 5% double-amplitude strain threshold (ε_{DA}) under cyclic loading, a criterion widely accepted by many researchers [22, 33]. Figure 10 presents the cyclic stress–axial strain hysteresis loops of the specimens. The specimen equilibrated at 5 kPa matric suction and 50 kPa net stress, with S_r = 50%, reached ε_{DA} = 8%, indicating cyclic failure under cyclic loading after 55 cycles. Examining the behavior of the UNC_15_50 specimen (S_r = 45%) under the same number of cycles, it was observed that axial deformations remained below 0.5%, and the specimen retained its rigidity. Figure 11 illustrates the pore pressure responses of the specimens to cyclic loading. In the UNC_5_50 specimen, which exhibited cyclic failure, both pore air and pore water pressures increased, with excess pore pressure buildup ratio ($r_{ua}=\Delta u_a/\sigma_{net}$, $r_{uw}=\Delta u_w/\sigma_{net}$) ranging between 0.40 and 0.50. This supports the conclusion that the specimen exceeded the threshold strain and reached failure. Conversely, in the UNC_15_50 specimen, pore air pressure remained unchanged, while pore water pressure exhibited a slight increase, with a pore water pressure ratio of approximately 0.20. Nevertheless, in agreement with the literature, pore water pressure increased more significantly than pore air pressure in both specimens [12, 16].

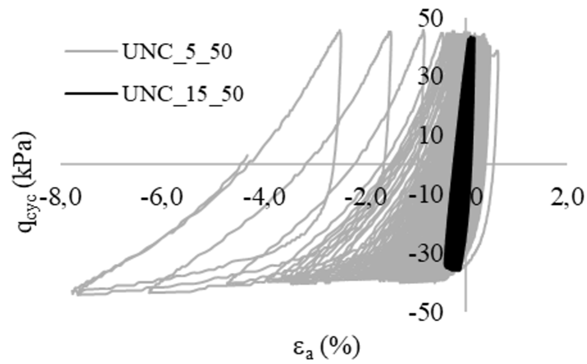

Fig 10. Cyclic stress-strain relations in different matric suctions.

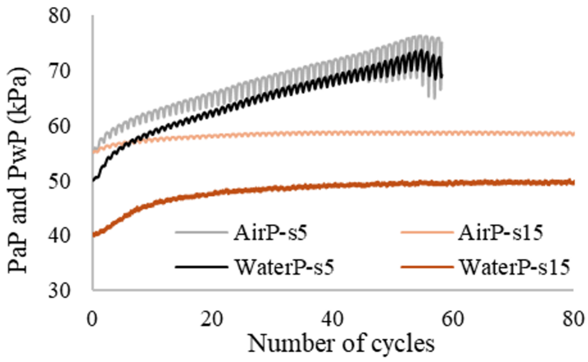

Fig 11. Pore pressures responses under cyclic loading in different matric suctions.

Figures 12-13 illustrate the axial and volumetric deformation behaviour of the specimens under cyclic loading. In the UNC_15_50 specimen, which did not experience cyclic failure, both axial and volumetric deformations remained below 0.5%. In contrast, the UNC_5_50 specimen exhibited axial and volumetric deformations exceeding 5%. It reached to DA=5% axial strain (cyclic failure) in 55 cycle. Looking at the graph it can be noted that, although the axial deformation response of the failing specimen was bidirectional in the initial cycles, it became increasingly concentrated in the tensile region as the number of loading cycles increased. A similar unidirectional accumulation of deformation behaviour was also observed in the studies of Kimoto et al. [12] and Tsukamoto et al. [18]. Examining the volumetric behaviour of the same specimen, it was found to exhibit significant volumetric contraction under cyclic loading.

4 Conclusions

The effect of matric suction on the behaviour of low-plastic silty soil was examined through monotonic and cyclic triaxial tests conducted on specimens prepared using the moist tamping method at similar void ratios. To isolate the influence of varying matric suction, all triaxial tests were performed under constant effective or net stress. Additionally, in cyclic tests, the specimens were subjected to the same cyclic stress ratio (CSR).

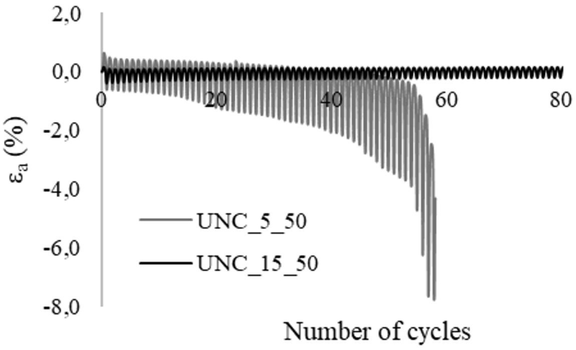

Fig 12. Axial strain behaviours with cyclic loading.

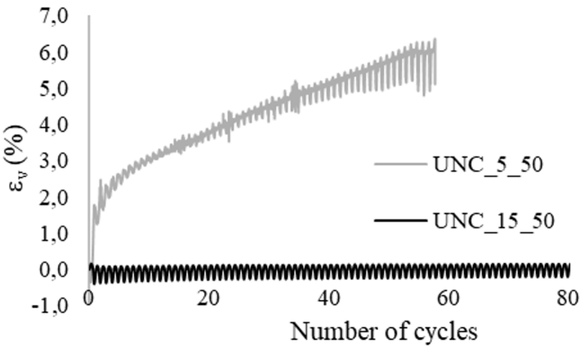

Fig 13. Volumetric strain behaviours with cyclic loading.

Under monotonic loading, an increase in matric suction led to an increase in strength, while the generated pore water pressures decreased inversely. The saturated specimen exhibited contractive behaviour, leading to failure, whereas the unsaturated specimens displayed dilative behaviour, with resistance increasing continuously as axial strain progressed. The results of the cyclic triaxial tests confirmed that matric suction is one of the parameters governing cyclic behaviour. At identical cyclic loading conditions, matric suction magnitude directly influenced pore pressure and deformation behaviour. The specimen with a 45% degree of saturation did not exhibit cyclic failure. Conversely, the specimen with 50% saturation experienced axial deformation exceeding 5%, leading to failure, despite pore air and pore water pressures not reaching confining pressure levels. Throughout cyclic loading, pore water pressure responded more rapidly than pore air pressure.

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