Research Paper

Effects of Specimen Saturation on Strength Reduction in Triaxial Tests: Monotonic and Cyclic Case Studies

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ABSTRACT

Degree of saturation of soil is an important factor in preparing specimens of soil in the laboratory. The moisture content of the specimen affects its behavior, especially in undrained loading, either by change of the structure of soil or by change of effective stress path. Even though a special equipment is required to measure the change of unsaturated specimen's geometry, they are not provided in many engineering laboratories due to economic and technical reasons. One alternative for a precise measurement is to saturate the specimens. We show herein that apart from such expensive measurements and saturating the specimens even though it is not saturated in the field, estimating the change of specimen size by simplifying the relevant assumptions and resembling the degree of saturation of the field in the laboratory is to be preferred. Two case studies of monotonic and cyclic triaxial tests are reported herein to show this priority based on field tests and image processing results. It is concluded that given the variation of the degree of saturation of the soil in the field, as well as its volumetric behavior while being sheared, that is, either being compressional or dilative, are essential to make the optimal decision on the selection of the proper degree of saturation at the laboratory.

Keywords:
Degree of saturation;
UU triaxial tests;
Unsaturated specimen;
Cyclic loading;
Compressional behavior;
Dilative behavior

1. Introduction

Soil specimens are usually saturated in the laboratory before they are consolidated in drained (CD) or undrained (CU) triaxial tests [1-2]. It is only the unconsolidated undrained (UU) test that does not require saturation before testing the soil specimen [3].

Effect of saturation on soil strength depends on the soil behavior while being sheared. If the specimen tends to contract in undrained shearing, its undrained strength decreases in saturated condition, while this is not the case in partial saturation condition. The reverse trend is observed for soils that tend to dilate while being sheared in undrained condition, i.e., the undrained strength of such saturated specimens is higher than that of partially saturated ones [4]. Consequently, it is necessary to consider whether the soil in the field experiences full saturation or not, and simulate the same situation in the laboratory.

In this paper, after a short review of the saturation effects on laboratory test results, recommendations are proposed to make the optimum decision on the degree of saturation of a specimen in the laboratory. Two case studies that support the recommendations idea are also reviewed herein.

2. Literature Review

Importance of simulating the soil's degree of saturation in the field in the laboratory has a long and clear history. Yoshida et al. [5] conducted several consolidated undrained triaxial tests on silty sand to silty clay specimens recovered from landslides caused by heavy rainfalls. It was shown that friction angle and cohesion decreased due to an increase in the degree of saturation.

One of the reasons behind different behaviors observed in soils with different degrees of saturation is suction. Chu and Chen [6] state that due to the effect of moisture on the characteristics of the soil, not only the moisture content of the soil in the laboratory should be identical to that of the field, but also the suction of the soil in the field should be simulated in the lab. Sun et al. [7] state that even if the same path of net stress and suction is followed while loading unsaturated specimens, the stress - strain relation and strength are different due to different degrees of saturation. They conclude that hydraulic and mechanical behavior of unsaturated soils should be considered simultaneously to predict its behavior precisely. Rosone et al. [8] also draw a similar conclusion after conducting triaxial tests on stiff and highly fissured clays. They recommend the degree of saturation to be included in the definition of the effective stress to obtain a satisfactory representation of the shear strength. Duong et al. [9] state that in plenty of cyclic triaxial tests on soil of railway substructure that is formed from inter-penetration of ballast and subgrade soils, the soil containing high fine-content has higher resilient modulus in unsaturated conditions, due to the contribution of suction. As the degree of saturation of soil increases, it loses its mechanical enhancement with a sharp decrease in resilient modulus. Dutta et al. [10] give an account of a reduction in shear modulus and an increase in damping ratio with saturation of compacted clayey soils, due to the suction present in the partially saturated soils. Wild et al. [11] report on the importance of the back-saturation of the clay shales that lost some degrees of saturation while being sampled and brought to the laboratory because saturation affected the structure and the capillary pressure inside the clayey soil they studied. Blackmore et al. [12] conducted cyclic triaxial and hollow cylinder tests on a typical railway formation material (clayey sand) and concluded that an increasing degree of saturation causes a decrease in resilient modulus of the soil due to the decrease in matric suction by saturation.

The above-mentioned overview assumes that the saturation does not change the structure of the soil. However, this assumption is not always true. Reznik [13] states that bearing capacity of loesses and loessial soils decrease with an increase in their porosity and water content, which necessitates proper field or laboratory tests to determine the deformation properties of collapsible soils. Rao et al. [14] state that partly saturated and highly porous laboratory-desiccated clayey silt specimens containing varying amounts of the cementitious iron oxides (hematite and goethite) are characterized by a metastable bonding provided by the capillary suction and crystalline iron oxides. When these specimens are soaked under surcharge, collapse of the laboratory-desiccated specimens occurs due to the loss of metastable bonding. The collapse potential of the soil is decreased by the increase in iron oxides content. Wong et al. [15] give evidence of the collapse of unsaturated silty clay soils while being saturated. The undisturbed specimens were sampled from landslides zones in tropical climates with heavy rainfalls. Major and minor principal stresses were maintained constant, and pore-water pressure was increased by water injection into the soil specimen in a triaxial cell, simulating slopes under heavy rainfall. Cho et al. [16] emphasize on swelling of clayey soils during saturation, which changes the structure of the soil. They recommend that the measured residual stress should be applied prior to saturating the soil. Elkady et al. [17] conducted consolidated undrained monotonic and cyclic triaxial tests on collapsible soils with different degrees of saturation. They observed a decrease in the static and cyclic strength of the soil by the increase in degree of saturation. Haeri et al. [18] mention that the collapsible soil they studied (unsaturated loessial Aeolian deposits) could experience pore collapse by substantial wetting of the soil. Wang et al. [19] state that as the moisture content of loess increases, its shear strength levels down.

3. Costly Instruments, Versus Simplified Estimates

In the literature review, the effect of degree of saturation on triaxial test results is confirmed, based on some examples from the literature. In unsaturated soils, suction affects the soil behavior. By an increase in saturation, suction decreases, and in some cases the structure of the soil changes by an increase in saturation. However, testing unsaturated soils needs extra considerations and equipment, as compared to the full saturated ones. In triaxial tests in which consolidation is conducted, it is easy to define the volume change of the saturated specimens by measuring the water expelled out of the specimen [1-2]. In this case, as the length change of the specimen is also measured easily by the aid of deformation transducers, the diameter change may also be calculated. However, if the specimen is unsaturated, the change of specimen length and diameter should be measured separately.

It is out of the scope of this paper to review the technics of measuring deformations of soils in a triaxial test thoroughly. There are a couple of instruments used for the measuring, such as collar strain gauges (clip gauges), local deformation transducers, proximity gauges, X-ray technics or optical deformation measurements. Lade [4] gives a thorough overview of these instruments in his book to be studied by those who are interested in further details. What we emphasis here is that, it is not practically possible to measure unsaturated soil's deformation precisely in engineering projects because laboratories are not equipped with the above-mentioned instruments. For economic and technical reasons, none of these instruments are a priority for laboratories. In the ASTM standard for unconsolidated undrained tests on cohesive soils [3], based on the assumption that lateral strains are equal to vertical strains, the average cross-sectional area for a given applied axial load is estimated by Equation (1):

$$A = \frac{A_0}{1-\varepsilon} \tag{1}$$

where A is average cross-sectional area and A_0 is initial average cross-sectional area of the specimen. ε is axial strain for the given axial load:

$$\varepsilon = \frac{\Delta H}{H_0} \tag{2}$$

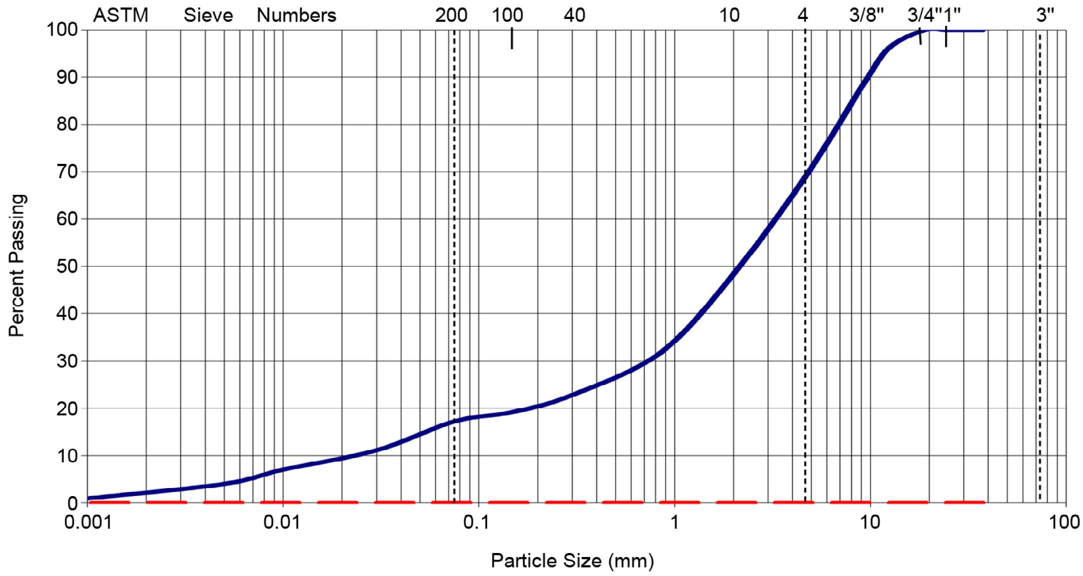
In Equation (2), ΔH is the change in height of specimen during loading. H_0 is initial height of test specimen minus any change in length prior to loading.

Consequently, the laboratories that are not equipped with instruments that measure the change of specimen-diameter during shearing should decide whether to assume that vertical and lateral strains are equal and keep the moisture content of the unsaturated specimens as they are in the field, or saturate the specimens to achieve more accurate measurements. This paper describes two case studies of triaxial tests, a monotonic and a cyclic one, conducted at the geotechnical laboratory of the International Institute of Earthquake Engineering and Seismology. In line with the literature, it is observed that the behavior of soils changes fundamentally as the degree of saturation changes.

3.1. Case 1: Monotonic Triaxial Test on Clayey Sand with Gravel in "North of Tehran"

Undisturbed samples were taken from a soil deposit in the north of Tehran, the capital of Iran, to design a deep excavation in the area. Figure (1) shows the gradation of the soil which was classified as SC, described as clayey sand with gravel [20]. Due to the oversized particles of the soil, field direct shear test was conducted at the site [21]. The natural moisture content of the soil was 7%, and 10% was required additionally to fully saturate the soil. Figure (2) shows results of the direct shear test in the field. Even though the figure shows proper soil strength, it was important to explore the soil behavior when saturated, in an identical condition in which it could occur in the field due to heavy rainfalls. Consequently, intact specimens were sampled to be examined in the laboratory. The specimens were extracted from the sampling tube carefully to have the least disturbance.

Figure (3) shows the axial stress-axial strain curves obtained from two UU triaxial tests on undisturbed samples taken from one sampler, called NT1 and NT2 herein. Specimen NT1 was tested with its natural moisture content (w=7%), and NT2 was fully saturated before being sheared (w = 17%). It is obvious in this figure that the

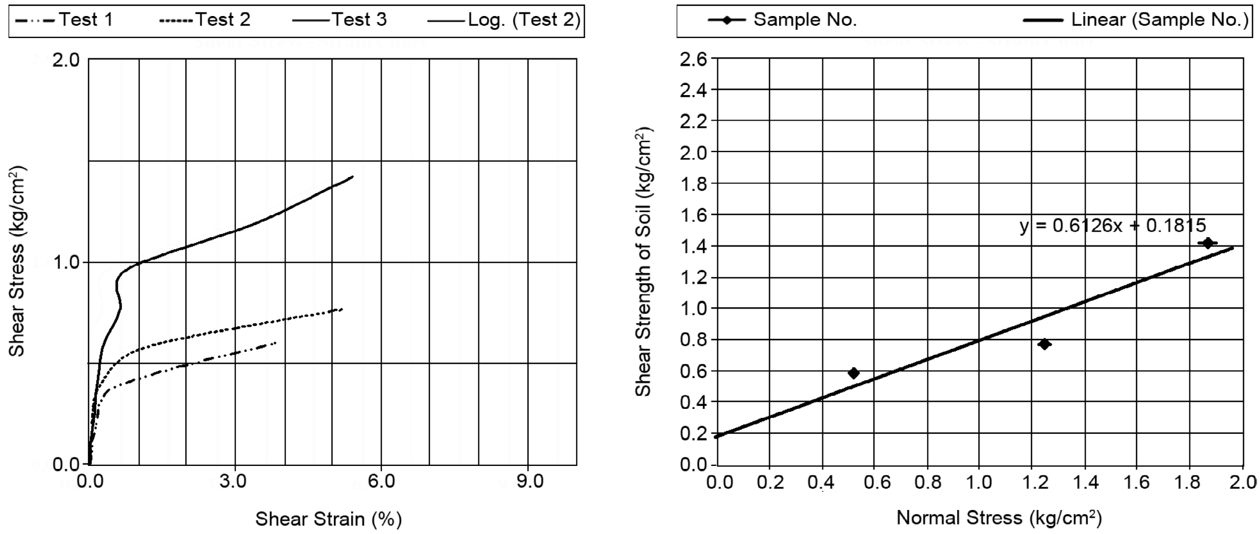


Silty and Clay	Sand			Gravel		Cobbles
	Fine	Medium	Coarse	Fine	Coarse	

Unified Soil Classification System						
Sample No.	Depth (m)	LL (%)	PI (%)	Group Symbol	Group Name	Legend
NT	2*1.5	26	8	SC	Clayey Sand with Gravel	

Figure 1. Particle size distribution and classification of the soil samples taken from "North of Tehran" project.

Project: North of Tehran	Sample No.:	Date: 2016/2/19	Location: North of Tehran
Depth (m): 6m	Type of Test: Direct Shear	Test Pit No.: TP-2-GL-2	Diameter (Square): 600mm



Height (m)	Normal Stress (kg/cm²)	Max. Stress (kg/cm²)	Shear Strain	C (kg/cm²)	f (Deg.)
6	0.52	0.58	0.58	0.18	31
6	1.25	0.77	0.77		
6	1.87	1.42	1.42		

Figure 2. Field direct shear test conducted at the site of the North of Tehran project [21].

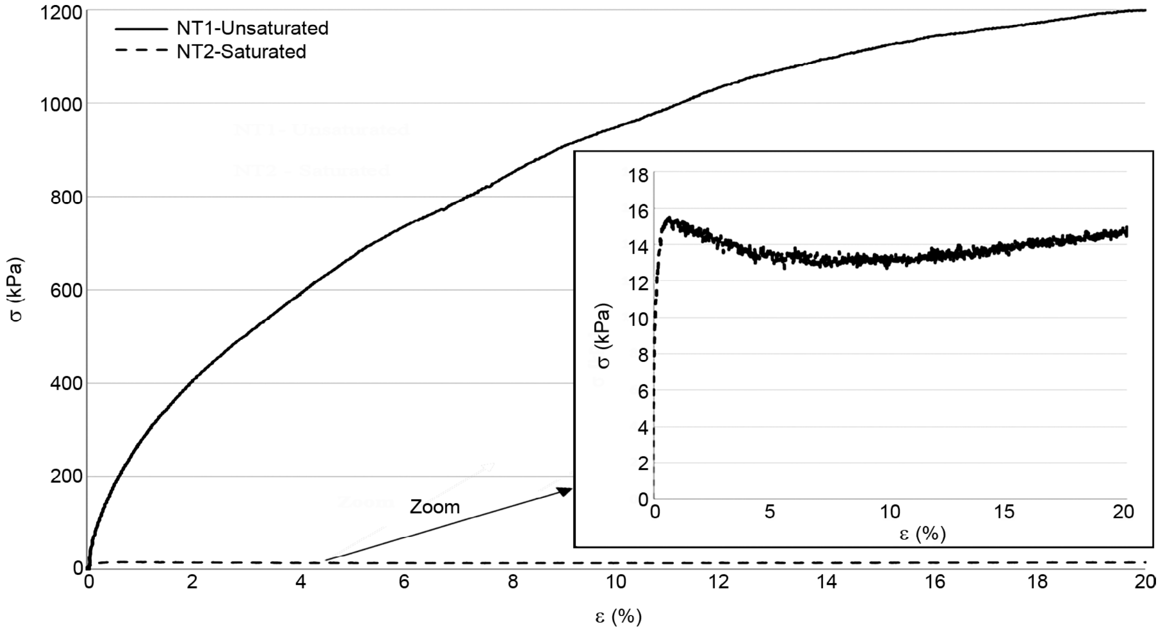


Figure 3. Variation of axial stress with axial strain in UU triaxial tests on unsaturated (NT1) and saturated (NT2) intact samples.

saturation nearly causes collapse of the NT2 specimen when a slight loading is exerted. Despite saturated specimen (NT2), the unsaturated one (NT1) tolerates a large amount of load, which could stem from suction as well as strong bonding among soil particles. These bonds are not easily broken by loading but disappear as moisture content rises.

It was then important to know how precise the assumption of equal vertical and horizontal strain was. Therefore, a UU test was conducted on another sample (NT3) from the same soil, and the loading process was captured by images that were processed [22] to extract precise dimensions of the specimen while being loaded. As shown in Figure (4), precise curves by image processing are maximally 7% different from the estimation, given the assumption of equal vertical and horizontal strains. The maximum deviation occurs at relatively large strains that are not practically significant in engineering designs, as these large strains are frequently beyond serviceability thresholds.

It is noteworthy that the image processing results are higher than estimates, which shows that the estimation leads to conservative strength parameters in this case.

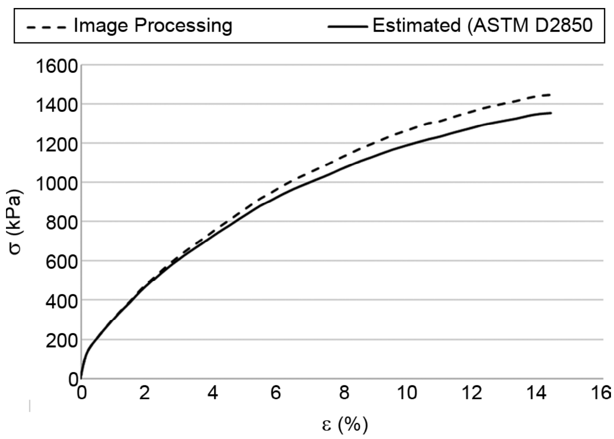


Figure 4. Variation of axial stress with axial strain in UU triaxial test on NT3 specimen, measured by image processing and estimated by assumption of equal vertical and horizontal strains.

3.2. Case 2: Cyclic Triaxial Test on Lean Clay in "North of Iran"

In another project in coastal regions of the north of Iran, plenty of cyclic triaxial tests were conducted on undisturbed samples of low plasticity clays, CL [20], to measure the potential of cyclic softening in the soft strata of the soil in the region. Due to the soft nature of the soil, care was taken to extract the specimens with the least disturbance, by wiring the sampling tube by a Fine toothed saw.

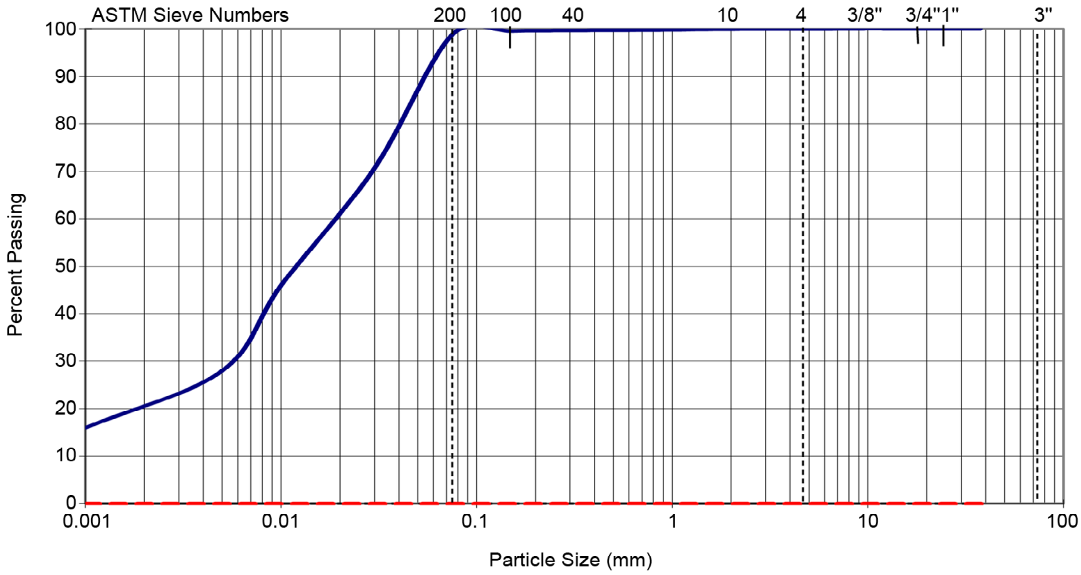
In some samples, saturation of the specimen was not successful and the pore pressure parameter B value (Equation 3) was below 0.95, which is the minimum value required for saturation [1].

$$B = \frac{\Delta u}{\Delta \sigma_3} \tag{3}$$

In Equation (3), Δu is change in the specimen pore pressure that occurs as a result of a change in the chamber pressure when the specimen drainage valves are closed. $\Delta\sigma_3$ is change in the chamber pressure.

Results of tests on two specimens that were sampled from one region and from similar depths of the strata, though saturated to different *B* values are presented herein.

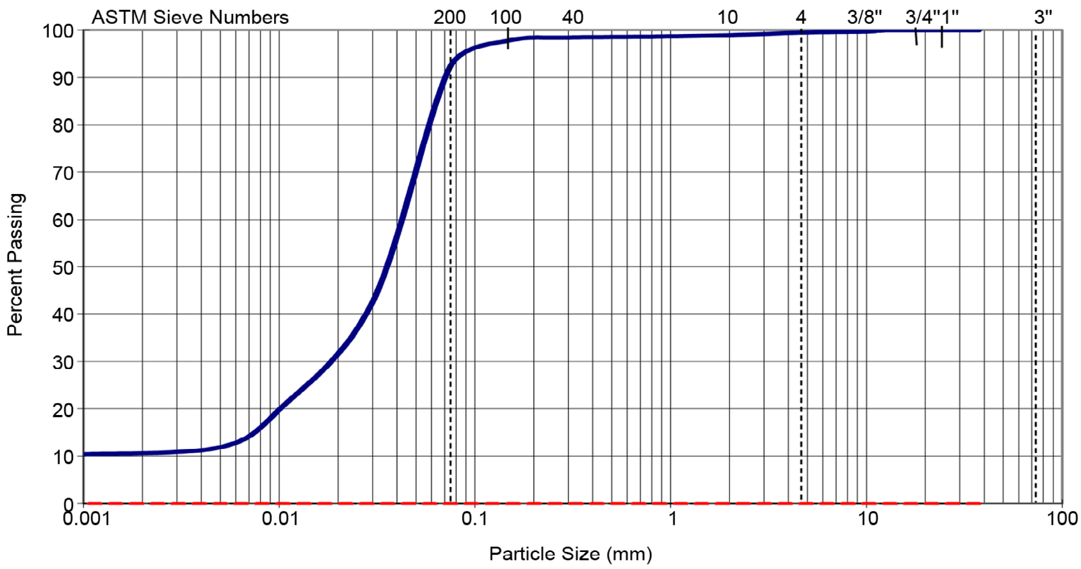
Figure (5) shows grading of the specimens. Table (1) also presents results of the classification



Silty and Clay	Sand			Gravel		Cobbles
	Fine	Medium	Coarse	Fine	Coarse	

Unified Soil Classification System						
Sample No.	Depth (m)	LL (%)	PI (%)	Group Symbol	Group Name	Legend
NI 1	4 m	36.1	17	CL	Lean Clay	

(a) Specimen NI1



Silty and Clay	Sand			Gravel		Cobbles
	Fine	Medium	Coarse	Fine	Coarse	

Unified Soil Classification System						
Sample No.	Depth (m)	LL (%)	PI (%)	Group Symbol	Group Name	Legend
NI 2	5-5.5	29.3	7.9	CL	Lean Clay	

(b) Specimen NI2

Figure 5. Particle size distribution and classification of the soil samples taken from "North of Iran" project: (a) Specimen NI1 and (b) Specimen NI2.

tests on both specimens. In this table, $CSR_{average}$ is the average cyclic stress ratio applied to the specimens, defined in Equations (4) and (5) [23].

$$Cyclic\ Stress\ Ratio\ CSR = \frac{\sigma_a}{2\sigma'_3} \tag{4}$$

Table 1. Specifications of specimens NI1 and NI2 in "North of Iran" project.

Specimen	NI1	NI2
Water Content [%]	33.5	25.5
Liquid Limit [%]	36.1	29.3
Plasticity Index [%]	17	7.9
B Value	40	90
USCS Classification	CL	CL
$CSR_{average}$	0.39	0.2
Number of Cycles to Reach ε_{sa}=3%	>220	83

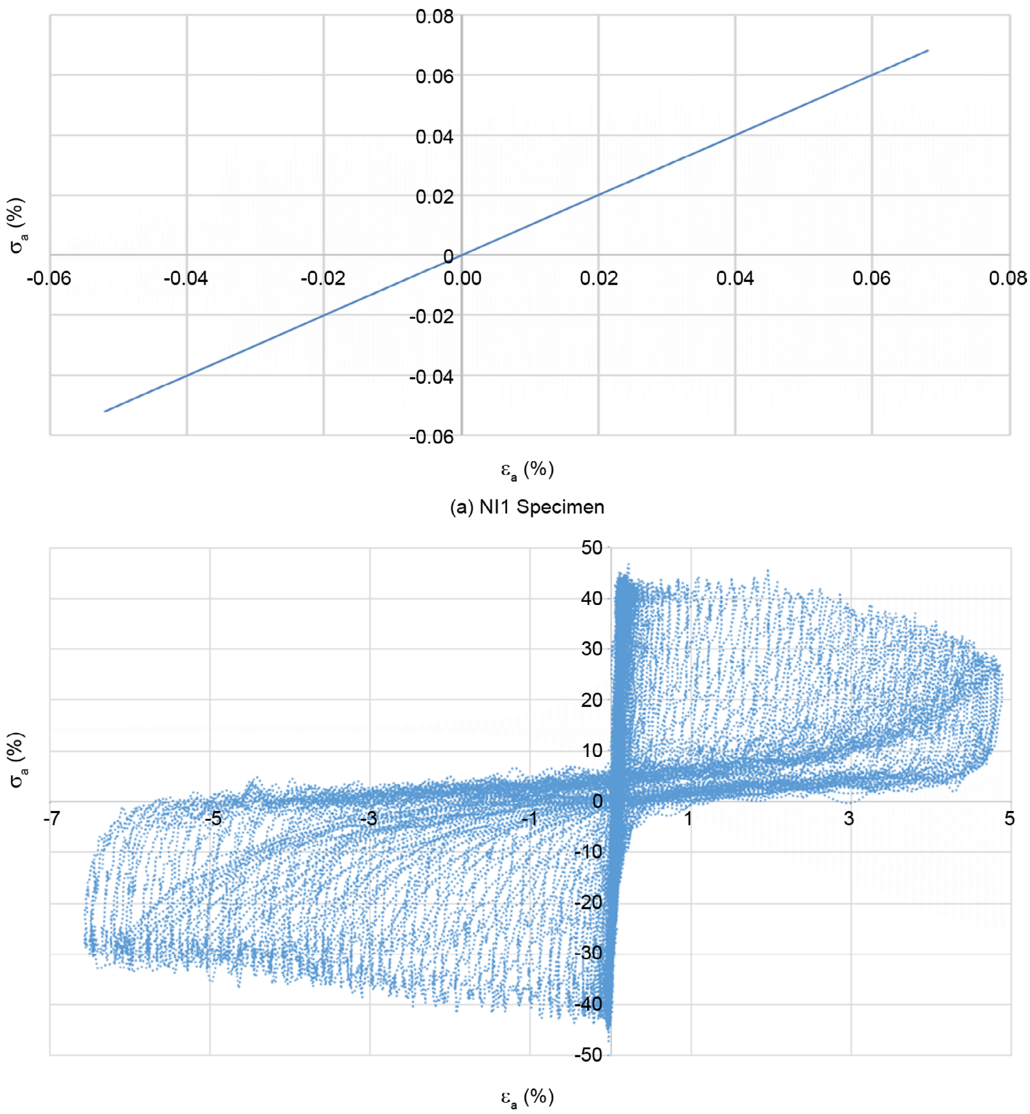
$$CSR_{average} = \frac{1}{m}\sum_{n=1}^{m} CSR_n \tag{5}$$

In Equation (5), CSRaverage is the average cyclic stress ratio up to cycle *m*, and CSR_n is the cyclic stress ratio in the n^{th} cycle.

Table (1) also includes ε_{sa}, which is single amplitude of axial strain, i.e., response of the soil to the applied CSR.

As depicted in this table, specimen NI1 is nearly unsaturated (B = 0.4), and specimen NI2 is close to full saturation (B = 0.9).

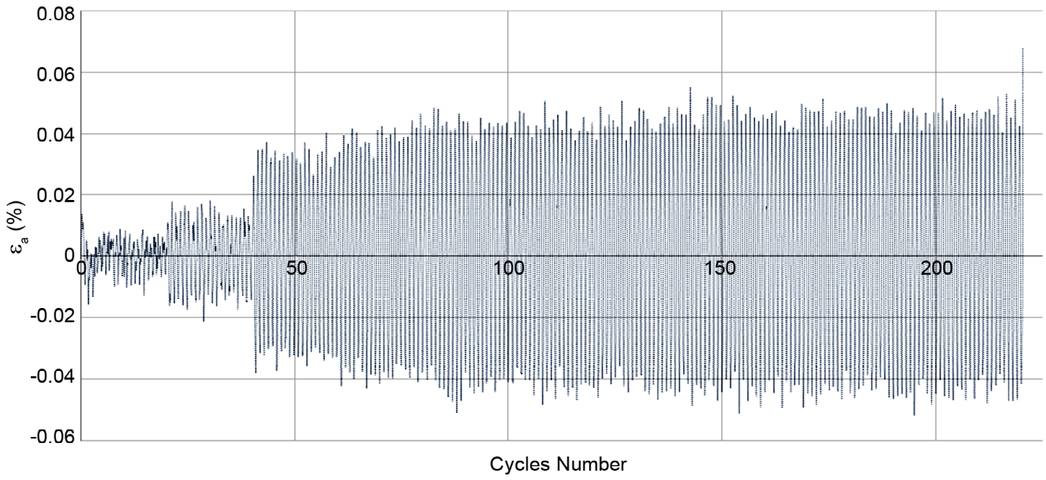
Figures (6) and (7) show the variation of axial stress and strain with cycles number, and the variation of axial strain with cycles number, respectively. It is observed that the specimen NI1 is stable under applied CSRaverage of 0.39, despite



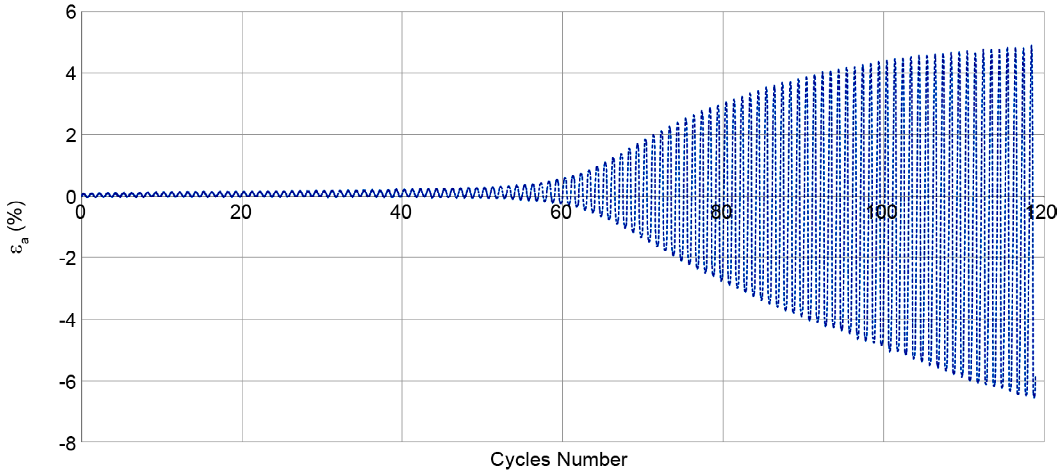
(a) NI1 Specimen

(b) NI2 Specimen

Figure 6. Variation of axial stress with axial strain in: (a) NI1 specimen and (b) NI2 specimen.



(a) NI1 Specimen



(b) NI2 Specimen

Figure 7. Variation of axial strain with number of cycles in: (a) NI1 specimen and (b) NI2 specimen.

the NI2 that reaches 3% single amplitude of axial strain after 83 cycles of a CSRaverage equal to 0.2.

This case study makes it clear that the degree of saturation plays the main role in the response of the soil to the applied cyclic loading. When the specimens were not saturated and low *B* values were attained, even several cycles of loading with relatively large values of CSR could not reach 3% single amplitude of strain, which shows that soil is stabilized. As soon as the *B* value became close to 0.9 or above it, the above-mentioned targeted strain was reached after some cycles, which means that the soil suffers from softening.

4. Discussion and Concluding Remarks

Degree of saturation is crucial in the response of the soils in the laboratory, even if the moisture content of the soil does not affect the structure. In case the water content changes the structure, the response of the soil may change drastically. The detailed review of the relevant literature on saturation effects on test results in this paper includes plenty of cases in which the strength of the soil reduces with the increase in its moisture content, due to the change of structure of the soil.

Overall, the loss of precision in measuring changes of diameter of the unsaturated specimens, due to the lack of relevant measuring devices, may not affect the σ - ε curves more than 14%. This limited deviation stems from the limited minimum and maximum thresholds of the Poisson's ratio. Figure (8) shows the variation of σ - ε in the test on NT3 specimen (Figure 4). In this figure, two more curves are added to the estimated curve (ASTM D2850) in Figure (4). The axial stress "σ" was recalculated according to the cross section resulting from diameter change in Equation (6).

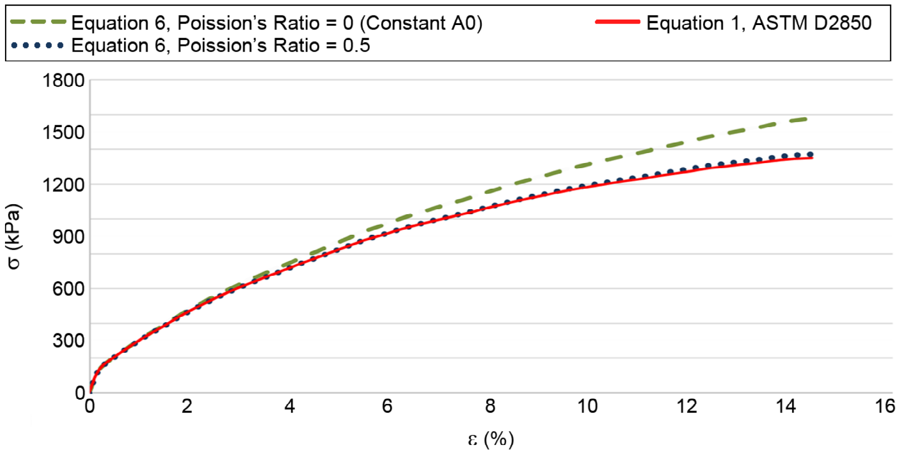


Figure 8. Variation of axial stress with axial strain in UU triaxial test on NT3 specimen, estimated by different assumptions for Poisson's ratio.

$$D = D_0 * (1 - \upsilon * \varepsilon) \tag{6}$$

In this equation, υ is Poisson's ratio and ε is the axial strain. Two curves regarding thresholds of υ, i.e., 0 and 0.5 are shown in Figure (8). These two curves are the thresholds of the σ - ε curves estimated in the unsaturated tests, with the assumption of Poisson's ratio. It is clearly observable that the maximum deviation is not more than 14%. It is also manifest that Equation (1) is the most conservative estimation of the diameter change of a specimen while being loaded in a triaxial test.

Two case studies of monotonic and cyclic triaxial tests were presented herein. They showed that an increase in the degree of saturation changed the soil behavior to extremely different categories. By the aid of image processing, it was also shown that in the absence of required instruments to measure change of specimen geometry in unsaturated condition, the estimation by assumption of equal vertical and horizontal strains gives conservative strength parameters in UU triaxial tests. Consequently, it is vital to resemble the degree of saturation of the soil in the field to measure precise results in the laboratory, even if the results are estimated by simplifying assumptions.

The case studies also reveal that the results of the field tests are not necessarily identical to the laboratory experiments on the same soil sample. Thus, an engineering judgment is required to come to a proper decision in the selection of soil characteristics for design purposes.

Last but not least, a conservative design should consider both/not only the real fluctuations of the degree of saturation of the soil during the life span of the targeted structure, but also the compressional or dilative behavior of the soil in the stress path that it may experience in the field. In this way, proper sample preparation in the laboratory in terms of the degree of saturation is possible.

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