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Influence of Matric Suction on the Shear Strength Behaviour of Unsaturated Sand

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As a part of the effort made to understand the behaviour of unsaturated soils, this work studies the shear strength characteristics of a cohesionless unsaturated soil. Generally, the determination of the shear strength of unsaturated soils is a great challenge to geotechnical engineers, both in terms of understanding it and the effort necessary to determine it. Matric suction is one of the stress state variables that control the shear strength of unsaturated soils. Therefore, the main aim of this study is to investigate the effect of matric suction on the shear strength characteristic of sand known commercially as Sand PR33. The shear strength behaviour of unsaturated sand is studied in this work using the constant water content triaxial test method with measurements of matric suction during the shearing stage. The tests were performed using the axis translation technique in such a way that the pore-air pressure was controlled while the pore-water pressure was measured during all tests.

Keywords: Unsaturated, suction, sand, triaxial, shear strength, axis translation technique.

1 Introduction

The development of soil mechanics for unsaturated soils began about two to three decades after the commencement of soil mechanics for saturated soils. The basic principles related to the understanding of unsaturated soil mechanics were formulated mainly in the 1970s [5]. Unsaturated soils have recently gained widespread attention in many studies and construction works all over the world, since many soils near the ground surface are considered unsaturated. The shear strength characteristics of unsaturated sedimentary and compacted cohesive soils have been the traditional subject of a number research studies in the last 30 years. Only a few studies have focused on analyzing the behaviour of unsaturated cohesionless soils (e.g., [3]). Recently, wide attention has been paid to the behaviour of unsaturated sand (e.g., [9] and [10]). In addition, many researchers have presented their results, when conducting constant water content triaxial tests (CW) on unsaturated soils, without analyzing the change of matric suction during these tests. Most of the studies have considered the matric suction inside the tested samples to be constant during the whole shearing process. However, the source of this assumption is unclear, as reported by Juca et al., [7]. Therefore, the decision was taken to study the shear strength behaviour of unsaturated sand using the CW triaxial test method with measurements of matric suction during the shearing stage.

2 Experimental work

2.1 Tested materials

Siliceous sand with grain size ranging from 0.1 to 0.5 mm and an average particle size of 0.32 mm was investigated in this study. The sand consists of about 7.0 % fine sand and nearly 93.0 % medium sand. It has a coefficient of uniformity of 1.20 and an effective diameter, D_{10}, of 0.21 mm. This sand is known as sand PR33, manufactured in the Czech Republic by Provodínské písky. It is purely cohesionless with a plasticity index, *PI*, of zero and a specific weight of 2.65.

2.2 Description of testing devices

To study the shear strength parameters and suction inside the tested sand, use of the triaxial apparatus was preferred, since it provides a three-dimensional load of the sample, which simulates the real load of the material in nature. An electronically controlled triaxial device was used after implementing some modifications that enabled the control and the measurement of matric suction inside the tested samples. The experimental testing program was executed at the Center of Experimental Geotechnics (CEG) at the Faculty of Civil Engineering of the Czech Technical University in Prague, using a 50 kN triaxial machine manufactured in England by Wykeham Farrance. As for all the other components of the triaxial apparatus utilized for this work, the computer-controlled compression machine was operated via a host computer using special software. Details and contents of the modified triaxial cell are shown in Fig. 1.

2.3 Identification of the testing program

A laboratory-testing program was planned and carried out to fulfill the objectives of this study. The testing program was divided into two main groups. The first group, GS, deals with samples that have 100 % degree of saturation (i.e., zero matric suction). The main goal of testing this group was to evaluate the effective shear strength parameters, c' and Φ', and to have the ability to compare the behaviour of saturated samples with that of unsaturated samples. Consolidated isotropic drained tests, CID, were utilized when testing the saturated sand samples. The identification of this group is summarized in Table 1.

Table 1: Layout and specification of group GS

Sample identity	Applied cell pressure, kPa	Applied pore pressure, kPa	Initial effective confining pressure, kPa
GS1	550	500	50
GS2	550	400	150
GS3	500	200	300

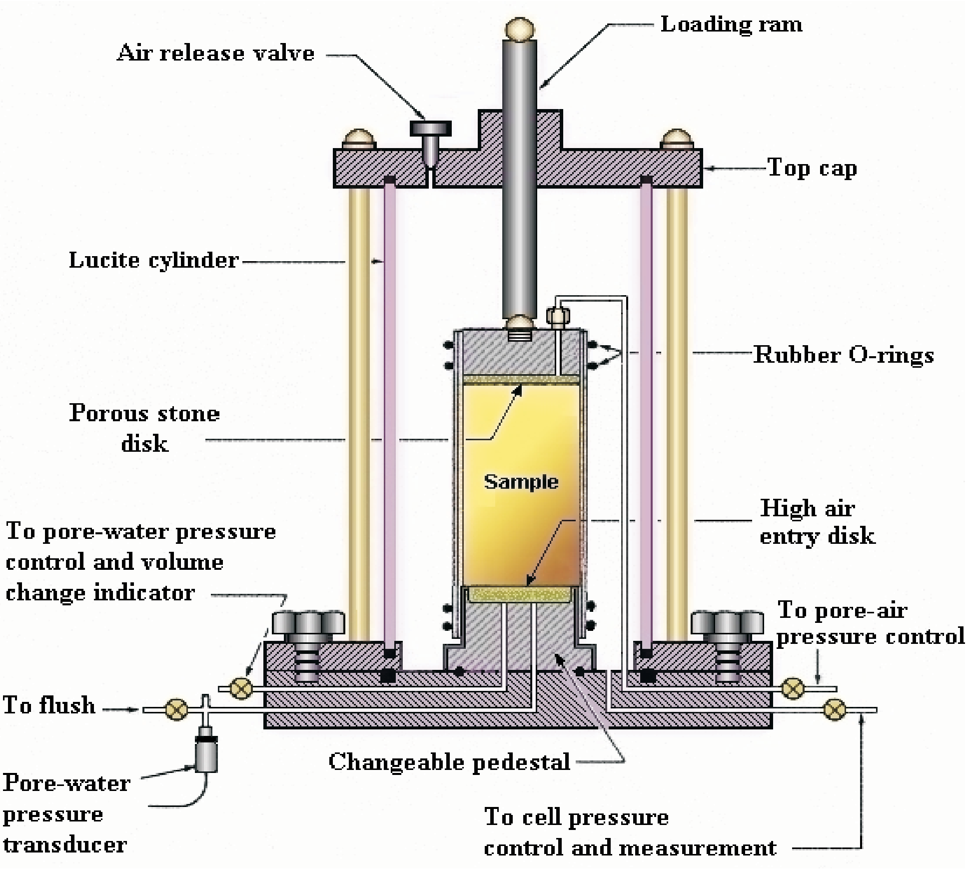

Fig. 1: Longitudinal cross section diagram of the modified triaxial cell for testing unsaturated soils

The second group, GUS, deals with unsaturated sand samples. Taking into account the air entry value of the high entry disk available in the laboratory, which was 150 kPa, a suitable range of matric suctions was chosen for this group. Three subgroups of samples with three different matric suctions, (30, 50, and 150 kPa), were tested in the triaxial apparatus using the constant water content test. Each of these subgroups consists of three samples having the same matric suction but tested under the effect of three different prescribed net normal stresses. During tests, the axis translation technique was utilized to maintain the desired matric suction inside the unsaturated samples and to prevent cavitation in the pore-water pressure measuring system. The pore-water pressure was measured, while the pore-air pressure was controlled, which provided the facility to measure the changes in matric suction during the shearing processes. Pore-water pressure, u_w, was measured at the base of the sample through the high air entry disk, while the pore-air pressure, u_a, was applied at the top of the sample through the porous disk. The values of the initial matric suction, the applied air and water pressures, the confining pressures, and other specifications are tabulated in Table 2.

Table 2: Layout and specification of group GUS at the end of the consolidation stage

Sample identity	Pore air pressure, (u_a), kPa	Pore water pressure, (u_w), kPa	Net confining pressure, ($\sigma_3 - u_a$), kPa	Initial matric suction, ($u_a - u_w$), kPa
GUS1-30	30	0	50	30
GUS2-30			150	
GUS3-30			300	
GUS1-50	50	0	50	50
GUS2-50			150	
GUS3-50			300	
GUS1-150	150	0	50	150
GUS2-150			150	
GUS3-150			300	

2.4 Preparation of samples

Samples were prepared from sand PR33 in its dry state without any other additions. The following procedures were similar when preparing both the saturated and the unsaturated samples. A suitable former consisting of a steel ring and a three-split mould, was used to maintain the required cylindrical shape of the specimens. The sand was dropped into layers inside a membrane fitted inside the mould. Each layer was compacted using a wooden rod until achieving the full height of the mould. After the sample had been leveled, capped and sealed, suction was applied to give sufficient strength and to make the sample self-supporting. This process led to cylindrical samples with a density of about 1.55 g·cm^{-3}. It should be pointed out that the full saturation condition (in the case of evaluating the effective strength parameters) or the required matric suction (in the case of testing the unsaturated samples) were not achieved at this stage. However, these conditions were achieved during the consolidation stage, as will be described later. Fig. 2 shows the main procedures followed to prepare the samples of sand.

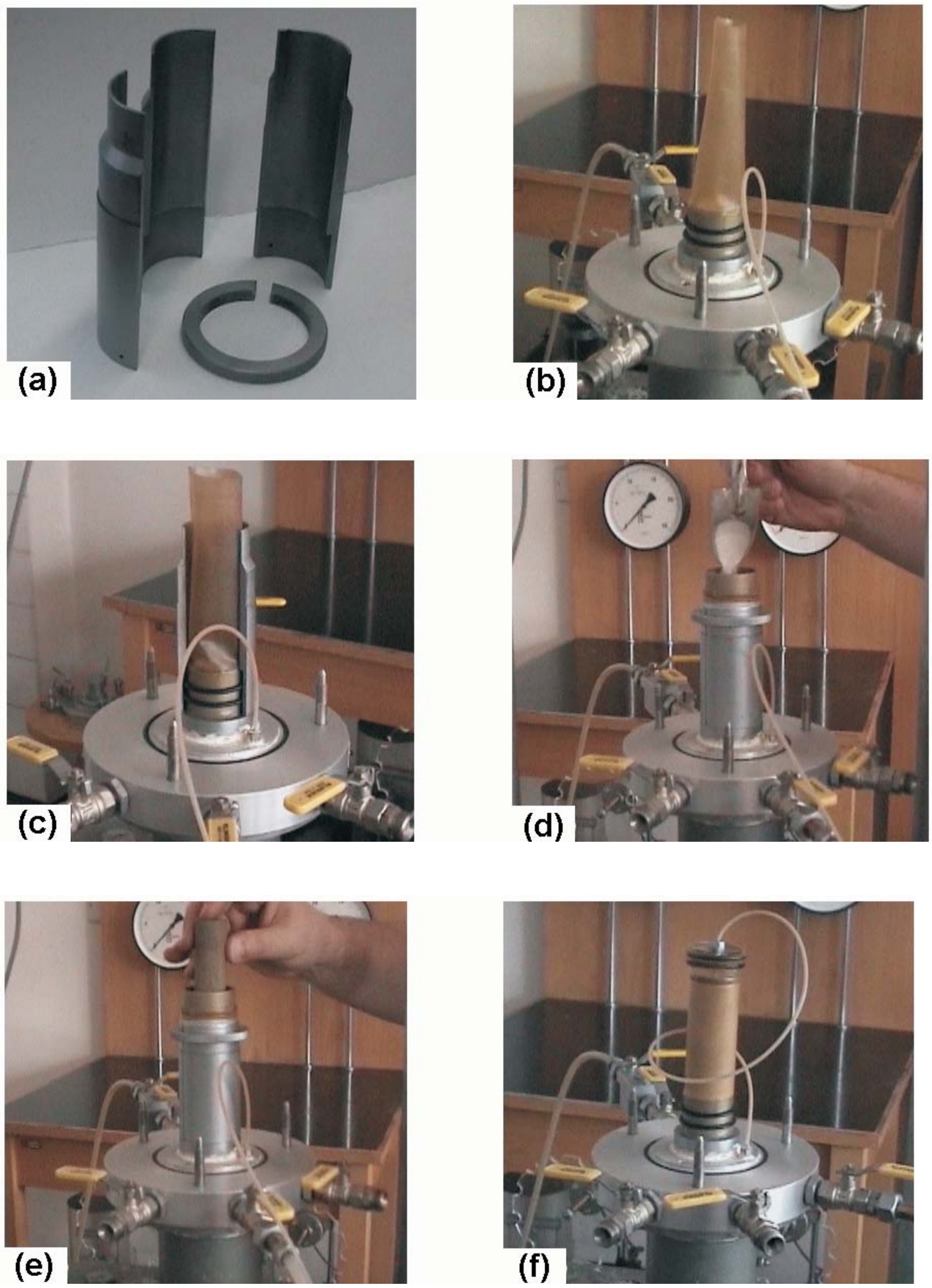

Fig. 2: Steps used for preparing the unsaturated sand samples, (a) the three split mould, and the steel ring; (b) fitting the rubber membrane around the triaxial pedestal and installing the lower O-rings; (c) assembly of the mould around the membrane; (d) filling the mould with sand PR33; (e) compaction of sand inside the mould; (f) sample ready to be tested

2.5 Testing procedures

During the consolidation stage, the samples were subjected to an all-round stress by pressurizing the water inside the cell at a prescribed confining pressure value. Two different types of consolidation stages were conducted according to the purpose of the test. Samples used to evaluate the effective stress parameters were consolidated against backpressure to produce saturation. The unsaturated sand samples with matric suction, $(u_a - u_w)$, less than 150 kPa were consolidated by applying a constant cell pressure and then imposing air pressure at the top of the sample, while the pore-water pressure was opened to the atmosphere at the bottom. This was done in order to control the matric suction inside the samples at prescribed values. Thereafter, with the confining pressure being held at a constant value after finishing the consolidation stage, the samples were sheared under strain-controlled conditions. The compression machine was set to a constant strain rate, and then was turned on to submit the axial load. During this stage, the pore-air pressure was maintained constant at the same pressure applied during consolidation, while the pore-water pressure was changing under the undrained conditions. This was achieved by closing all valves except for those that supplied the air and the cell pressures. In such conditions, this test is known as the constant water content triaxial test, CW, since no water was allowed to drain during the shearing stage. The net confining pressure, $(\sigma_3 - u_a)$, remained constant during this stage, while the matric suction, $(u_a - u_w)$, varied. To ensure equalization of pore pressures throughout the samples, the shearing process was performed at a strain rate of 0.03 mm·min^{-1} (i.e., approximately 0.034 % min^{-1}), which was less than or coincided with those rates suggested for similar tests and similar type of soil by many researchers, e.g., [4], and [2].

3 Test results and discussions

The results showed that the increase in matric suction did not affect the general shape of the stress–strain relationship. Thus, for the whole range of the applied matric suction, the shapes of the stress–strain curves for unsaturated samples resemble those for saturated samples. It was also observed that at the same net confining pressure, the strength of an unsaturated sample is greater than that of a saturated one. For example, Fig. 3 shows that the shear strength of sample GUS1-50 is roughly 1.25 times that of saturated sample GS1, which indicates that an increase in soil suction leads to an increase in shear strength.

The interpretation of this phenomenon is that, at low matric suction, air enters the pores and a contractile skin begins to form around the points of contacts between particles. The capillary action arising from suction at the contractile skin increases the normal forces at the inter-particle contacts. These additional normal forces may enhance the friction and the cohesion at the inter-particle contacts. As a result, the unsaturated sand exhibits a higher strength than the saturated sand. However, this does not seem to be the dominant behaviour for the whole range of the applied matric suction. When comparing the maximum deviator stress values in the case of a sample exposed to matric suction of 50 kPa with those of 150 kPa, it can be seen that the maximum effect on the deviator stress and shear strength is reached at matric suction of 50 kPa. It was observed that after this value, the increase in maximum deviator stress, $(\sigma_3 - \sigma_1)_{\max}$, drops away. This behaviour indicates that, during the consolidation process, as the matric suction increases to a relatively high value, the sand begins to dry and the water menisci start to accumulate only between fewer grain particles. The interpretation of this behaviour can be that, at low matric suction, air replaces some of the water in the large pores between the grains, which causes the water to flow through the smaller pores and forms water menisci at the grain contact points. In addition, it is well known that, unlike clayey soils, sand has a very low ability to sustain water menisci between the particles. This is due to the fact that, in coarse-grained soils, water exists mainly as free pore water, while in fine-grained soils the water adsorbed on particle surfaces becomes dominant [8]. Accordingly, at higher matric suction values, a further decrease in water that occupies the pore volume of the studied sand will take place during the consolidation stage, which leads to a further decrease in the number of connections between the water and sand particles. The total contact area of the momentary contact surfaces arising from the water menisci may be radically

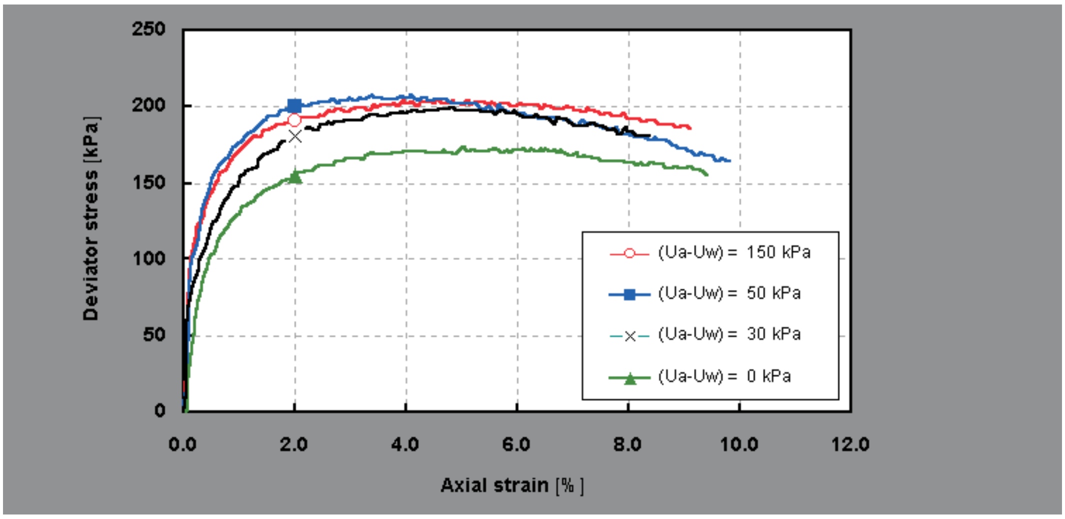

Fig. 3: Stress-strain curves for sand PR33 at various matric suctions under the effect of 50 kPa net confining pressure

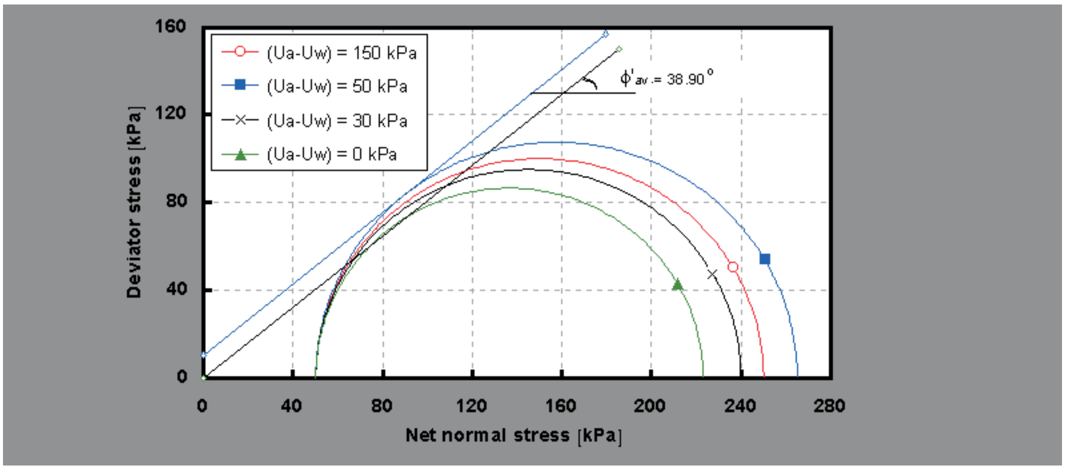

Fig. 4: Mohr circles for sand PR 33 at various matric suctions under the effect of 50 kPa net confining pressure

decreased also as a great amount of continuous air phase is formed throughout the soil. Thus, the total number of water menisci, which act as a glue at the grain contact points, will be fewer than the number at lower matric suction. As a result, the amount of increase in the strength of the studied sand begins to drop.

To clarify the effect of matric suction on increasing the strength of the studied sand, four sets of Mohr circles representing four samples, which were all studied at 50 kPa net stress but at four different matric suctions, are plotted in Fig. 4. However, this figure shows that the general trend of increasing shear strength with matric suction of sand is not so quite evident as it is for clayey or silty soil. The failure envelopes intercept on the ordinate equal to $c = 0$, 8.76, 11.51, 7.36 kPa for matric suction of 0, 30, 50, 150 kPa, respectively.

The variation of matric suction under the constant water content condition during the shearing stage is investigated here. Matric suction versus axial strain curves are presented in Figs. 5 and 6. In general, these figures show that matric suction decreases as the shearing process develops. This result can be attributed to the fact that pore-air pressure is maintained at a constant value while the pore-water pressure increases continuously during shearing of the sample. Thus, the degree of saturation of the sample is expected to increase, since the pore-air is squeezed out of the soil while the water content remains constant. The change in matric suctions at failure in the case of a sample tested using initial matric suction of 50.0 kPa ranged from approximately 5.0 kPa for sample GUS1-50 to nearly 20.0 kPa for sample GUS3-50 (i.e., from 10 % to 40 %). Similarly, the change in matric suction at failure for samples tested using initial matric suction of 150.0 kPa ranged from 20.0 kPa for sample GUS1-150 to approximately 50.0 kPa for sample GUS3-150 (i.e., from 12 % to 35 %).

Furthermore, Figs. 5 and 6 show that for the whole range of the net confining pressures used in these tests, the change in matric suction in the case of tests conducted at 50 kPa initial suction is more gradual than in those conducted at 150 kPa, which shows much steeper behaviour. This can be related to the procedures followed in this study to apply the desired matric suction into the tested samples (i.e., the axis-translation technique). It is well known that the axis translation technique is usually performed by increasing the pore-air pressure, u_a, which in turn increases the pore-water pressure, u_w, by an equal amount. Although the pore water pressure was

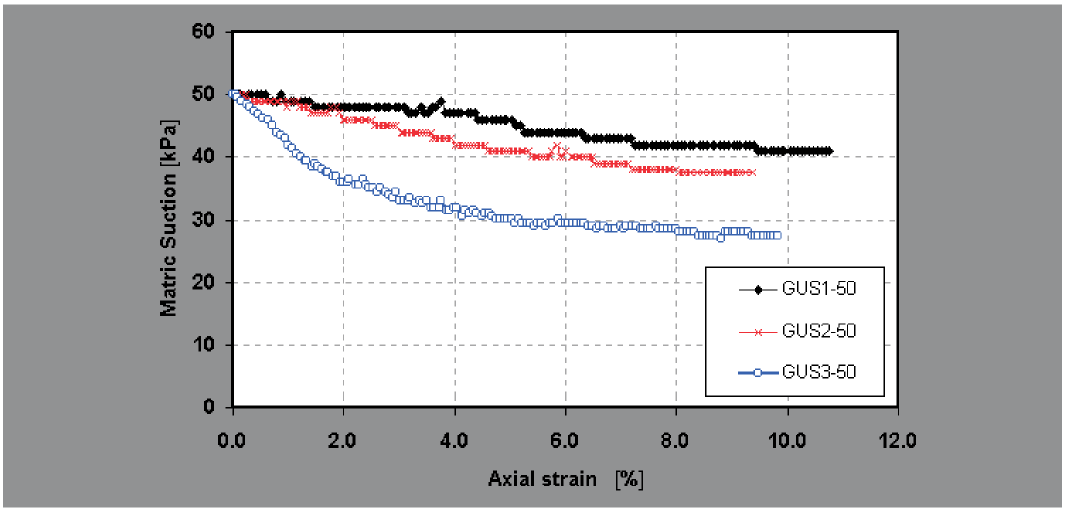

Fig. 5: Variation of matric suction during shearing process of group GUS-50 under constant water content conditions

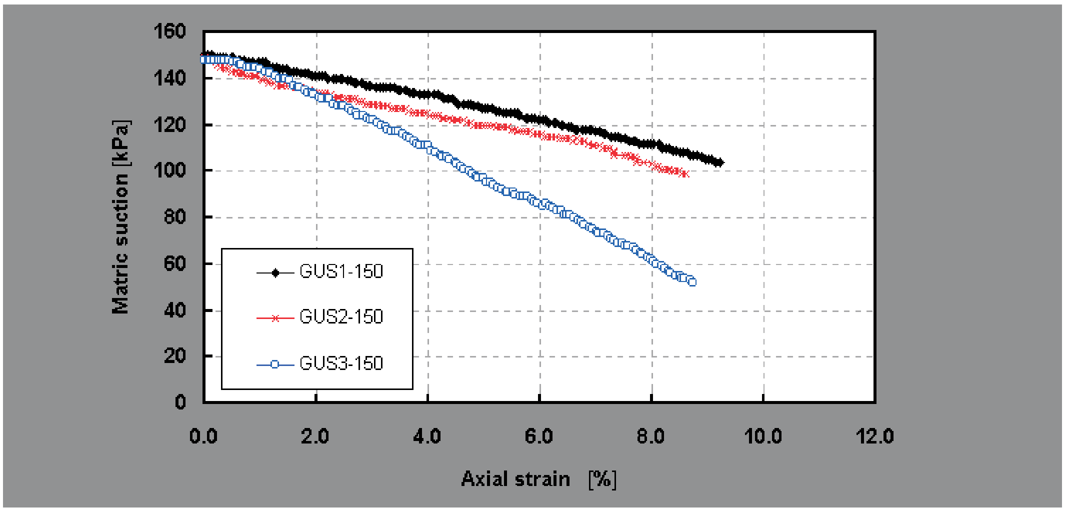

Fig. 6: Variation of matric suction during shearing process of group GUS-150 under constant water content conditions

controlled to be atmospheric during the whole consolidation stage, this surely was not the case during the shearing process under constant water content conditions. That is why, during shearing of the samples, the high air pressure applied to samples GUS-150 in order to have 150 kPa initial matric suction increased the pore water pressure much higher than that inside samples GUS-50, which were exposed to lower air pressure to have initial matric suction of only 50 kPa.

In addition, it can be seen from Figs. 5 and 6 that under the same initial matric suction condition, the variation in matric suction for samples under higher net confining pressures is much more pronounced than the variation for samples under lower confinements. Similar observations were reported by Adams et al. [1], Herkal et al. [6] and Wulfsohn et al. [11]. However, it seems that using high net confining pressures during the constant water content shearing stage reduced the volume of the sample. This is largely attributed to the fact that higher net stresses cause a greater reduction in the pore spaces (i.e., compression) during the preceding isotropic consolidation stage, which causes the particles of the sample to be in a closed packed form. Under these conditions, pore-air and pore-water may become entrapped and thus less air will be expelled, which increases the pore water pressure as a result of shearing the sample while the pore-water phase is in the undrained mode. Thus, a significant variation in matric suction for samples tested under high confining pressures will be attributed to the build up of pore water pressures within the samples.

4 Conclusion

The results obtained from a series of triaxial tests performed on sand in its unsaturated form indicated that the shear strength of the samples increases as a result of increasing matric suction. However, this did not seem to be the dominant behaviour for the whole range of the applied matric suctions. In fact, the maximum effect on the shear strength was reached at a certain value of matric suction, and then the increase in strength drops. The results showed that unsaturated sand could attain some cohesion although the effective cohesion is equal to zero. Furthermore, testing the unsaturated sand showed that the variation in matric suction during tests for samples tested under high net confining pressures is much more pronounced than that for samples under lower confinements. Thus, it is recommended when performing triaxial constant water content tests on unsaturated soils, to perform tests using low net confining pressures to minimize the differences between the initial matric suction and the matric suction at failure.

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