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Insight Into Soil Cyclic Triaxial Testing Using a High Capacity Tensiometer

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Abstract

Unsaturated soils often form part of geo-infrastructure such as road and railway substructures subjected to repeated traffic and train-induced loading. However, the principles of Unsaturated Soil Mechanics have commonly been neglected in design protocols of such infrastructure mainly due to the lack of appropriate experimental data and poor understanding of the response of unsaturated soils to complex loading. Advances in suction measurements using tensiometers have enabled practical analysis of the behaviour of unsaturated soils under laboratory and field conditions. This paper discusses the advantages of using a high-capacity tensiometer in studying the cyclic response of unsaturated clayey sand taken from a railway formation. The tests were carried out using a cyclic triaxial apparatus while suction was continuously monitored during testing using a tensiometer mounted on the body of soil samples. The soil cyclic behaviour including accumulated axial strains and resilient modulus was observed to be dependent on the soil suction levels as well as the confining pressure and cyclic deviatoric stress applied. The Bishop's stress ratio (defined as the ratio between the cyclic deviatoric stress and mean Bishop's stress) was used to interpret the test results where the accumulated axial strain was consistently found to increase and resilient modulus to decrease with the Bishop's stress ratio.

Keywords: suction measurement, triaxial testing, resilient modulus.

1. Introduction

Cyclic triaxial testing apparatus are often used to investigate the cyclic response of compacted formation soils of roads and railways. Although many researchers have focused on understanding the dynamic response of formation soils under saturated conditions (Shahu et al., 1999), the soils used within railway embankments usually lie above the ground water table and remain unsaturated during their operational life. Therefore, their dynamic response in terms of cumulative plastic deformations and cyclic stiffness (ratio of the cyclic deviatoric stress to the resilient strain) needs to be assessed within the framework of Unsaturated Soil Mechanics. In addition, as climate change increases severe weather events geo-infrastructure will become more vulnerable and a full understanding of the behaviour of their formations under climatic loading can help to develop a strategy to mitigate climate risks and provide resilient infrastructure. The impact of frequent rainfall and drought continuously alters the water content and suction within subgrade soils (Brown, 1996). The variation of water content together with dynamics of traffic can aggravate the cumulative deformation and dynamic resilience of subgrade soils (Blackmore et al., 2020). The application of the principles of Unsaturated Soil Mechanics at the design stage while considering fluctuating water conditions requires the continuous measurement of suction, water content and volume change during cyclic loading (Azizi et al., 2021; 2022). This is essential to understand the dynamic nature of hydro-mechanical behaviour of soils (Kumar et al., 2022a,b).

In recent years, modified cyclic triaxial testing systems equipped with various instruments (thermal dissipation sensor, psychrometer, suction probe, axis-translation technique, etc.) have been used to measure or control the soil suction during cyclic tests to obtain reliable results on the variation of the resilient modulus with soil suction (Ng et al., 2013; Sivakumar et al., 2013). Such modified triaxial testing systems are expensive, cumbersome, and require trained professionals to conduct the tests. In addition, a relatively long testing time are typically required to achieve water equilibrium conditions with respect to each applied suction value, particularly for fine-grained unsaturated soils, if suction-controlled techniques such as the axis-translation technique are employed. In addition, this process does not actually correlate with the actual field conditions where air pressures are atmospheric and water pressures are negative (Toll et al., 2013). The drawback of the axis translation technique is preventing cavitation, which naturally occurs in unsaturated soils, but cannot occur when the water pressure is in the positive range. The other shortcoming is the low permeability of the ceramic porous stone used in axis translation which causes a delayed response of pore water pressure measurements when being used to measure suction. Moreover, the water pressure is measured at the end of the sample, hence the pore pressure values may not be representative of suction along the height of specimen during loading cycles. Researchers have used the thermocouple psychrometer technique to measure suction during cyclic triaxial testing but this technique may not be accurate as it is an indirect measurement of suction (Thom et al., 2008). The advent of high capacity tensiometers to measure suction under natural conditions has brought a shift in understanding and explaining the behaviour of unsaturated soils (Ridley and Burland, 1993, Toll et al., 2013; Azizi et al., 2020). This is mainly because of faster response time, direct suction measurement and easy maneuverability due to the miniature size. The time to obtain readings is of the order of seconds and minutes compared to days using axis-translation and filter paper techniques. Although the tensiometer has started to become commonly used for soil laboratory testing, direct measurement of suction using a tensiometer during cyclic triaxial testing has not been investigated by other researchers.

The research reported in this paper describes the use of a high-capacity tensiometer during cyclic triaxial testing of a clayey sand subjected to a cyclic deviatoric stress at a constant confining pressure. Direct measurement of suction was carried out at the mid-height of the sample allowing the interpretation of water retention paths evolving during the different stages of testing. It is to be noted that suction changes would be more evident around the location of the intense shearing strain that occurs at sample mid-height, as cycles of the deviatoric stress will cause changes in the volumetric strain. Hence, to record suction change consistent with the volumetric strain, local suction measurement around the centre of the sample was adopted. The obtained results are discussed in terms of accumulated strain, suction and resilient modulus of soil.

2. Material description and sample preparation

The material tested was collected and transported to the UK from South Africa where it was obtained from the 650 km heavy-haul coal line. The material was class B subgrade (400 mm thick) as described by South African Transnet S410 specification of railway earthworks, and was sand containing 6% clay. The soil was oven dried and mechanically ground. The ground soil was mixed with 10.8% of water content (wet side of optimum) and sealed in a plastic case for 24 h to allow for water homogenisation. The wet soil was placed in a Proctor mould and dynamically compacted using a standard Proctor rammer in 4 layers to obtain a more homogenous sample. The sample of diameter 70 mm and height 140 mm was then extruded for testing.

Prior to testing, specimens used for unsaturated testing were subjected to drying and wetting cycles to understand the effect of varying hydraulic changes on the cyclic behaviour of the materials. Prior to testing, samples were subjected to air drying in a laboratory environment and wetting within a closed humidity chamber using a fogger. The weight and dimensions of the specimen were monitored at a definite interval to track the changes in the water content and the volume. A negligible radial strain was induced during these wetting and drying processes. During each step of drying and wetting, the sample was wrapped for moisture equilibration. These processes helped in obtaining samples at different suction and water content.

3. Experimental Methodology

The double-cell wall dynamic triaxial apparatus capable of performing stress controlled cyclic loading with on-sample arrangements was modified to allow direct measurement of suction by a high capacity tensiometer (Kumar et al. 2022b). The tensiometer used was developed at Durham University capable of measuring pore-pressure changes in positive and negative ranges up to 2000 kPa. The GDS triaxial equipment is capable of performing stress and strain-controlled cyclic triaxial testing on soil samples with different sizes; in this study specimens having a diameter of 70 mm and height of 140 mm were used. On-sample instrumentations including axial and radial displacement transducers were used to measure the volume changes during the testing stages.

The tensiometer was mounted just above the mid-height of the sample to allow space for on sample displacement transducers. An access hole was cut in the latex membrane to allow for an intimate contact of tensiometer with the soil. A rubber grommet was used to mount the tensiometer on the soil specimen through the access hole. Three coatings of Silica gel were applied all around the access hole to seal the cut. A gap of approximately four hours was maintained while applying the coating of the silica gel to obtain a uniform and intact seal. Further details about the installation of on-sample instruments are mentioned in Kumar et al. (2022a,b). Figure 1 shows a photograph of the GDS triaxial apparatus and a sample with on-sample instrumentation used in this study.

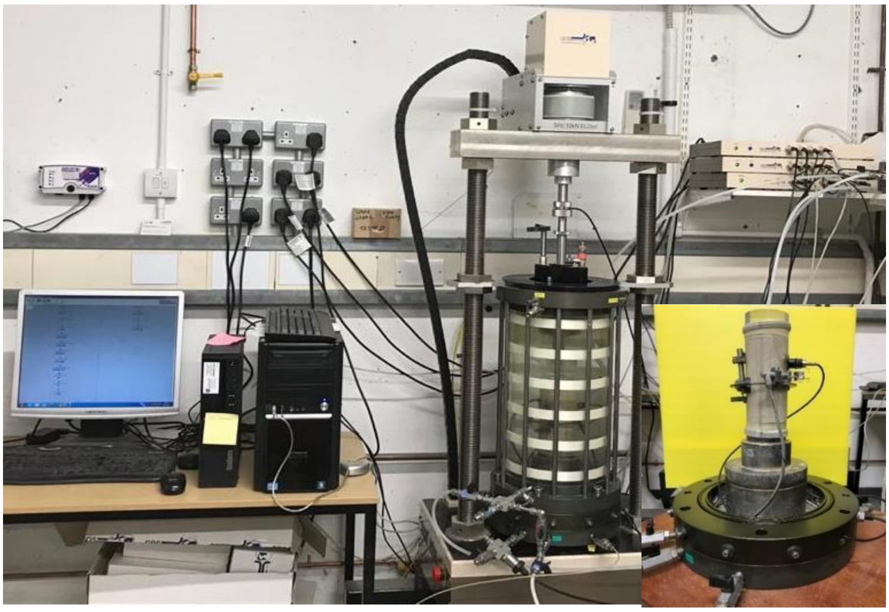

Figure 1: Photograph of GDS triaxial testing apparatus and on-sample instrumentation.

4. Suction monitoring prior to testing

Figure 2a shows suction readings during the assembly process for two specimens that achieved equilibrated suction readings of 140 kPa and 259 kPa, values that were achieved after 200 mins and 300 mins, respectively. The elapsed time required for suction equalisation was high because a wet soil paste was used at the sensing face of tensiometer to ensure good contact between the soil and tensiometer. The paste was fully saturated and at about zero suction at the time of installation and needed to attain the suction level of the soil sample to attain suction equilibration. In addition, a sample with higher suction value took longer time than the sample with lower suction value to attain the equilibrated suction. The fluctuations in the reading were mainly due to the disturbance caused during the repetitive application of the silica gel seal to fix the tensiometer and make the membrane waterproof. After a constant value of suction was observed, the triaxial cell was filled with water. Figure 2b shows the changes in the suction readings after the application of a confining pressure of 20 kPa in a specimen with an initial suction of 140 kPa. It can be observed that the suction reduced from 140 kPa to 122 kPa after the application of confining pressure. It is to be noted that the confining pressure was increased gradually to allow suction to equalise with time. The reduction in the suction values was mainly due to the volumetric compression brought about by the confining pressure which reduced the void ratio of the sample leading to an increment in the degree of saturation at the constant water condition. The cyclic deviatoric stress was applied after the attainment of the equalised suction reading under a constant value of the confining pressure.

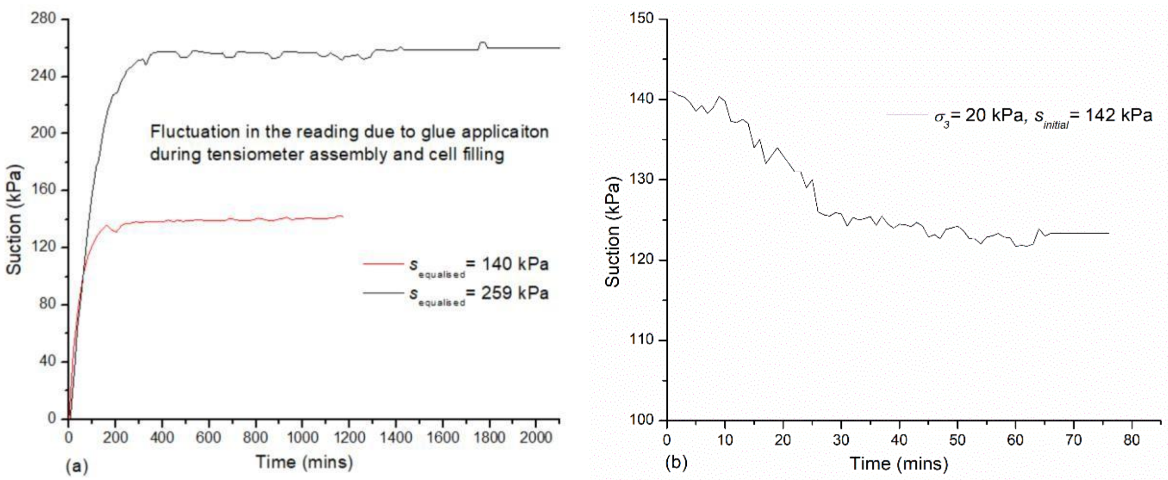

Figure 2: Suction equalisation reading under different stages (a) installation (b) compression.

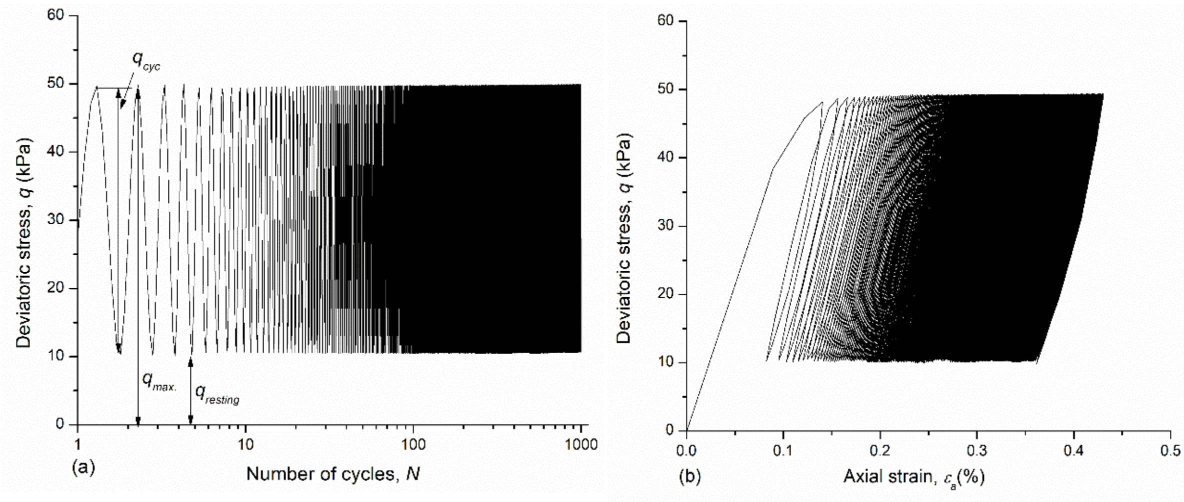

Figure 3: Deviatoric stress vs. (a) number of cycles (b) axial strain.

5. Cyclic testing methodology

The cyclic deviator stress q_{cyc} of 40 kPa representative of the actual field condition of the subgrade B level as reported by Gräbe (2005) was applied. A resting stress of 10 kPa was maintained throughout the test to simulate the dead load from the rail superstructure and the ballast. The number of loading cycles applied during each test was 1000 which was sufficient to bring the resilient response of the soil sample indicated by evolution of only recoverable strains and negligible permanent strains. Figure 3a shows the typical cycles of the cyclic deviator stress of 40 kPa while a cyclic loading frequency of 1 Hz was applied to the sample. Figure 3b shows the typical accumulation of axial strains under the applied cyclic deviatoric stress which indicates that the changes in the permanent strain reduces after a few cycles and the permanent strain remains almost constant during the following cycle.

6. Results and discussions

6.1 Suction and resilient modulus

Figure 4 shows the results of variation of suction and resilient modulus for two tests conducted under confining pressure σ_3 of 20 kPa and cyclic deviator stress q_{cyc} of 80 kPa. The test identified as As indicates "as compacted" (at a water content of 10.8%) and 1D indicates a test carried out after one drying cycle (at a water content of 6.16%). The suction reduction and then equalisation (Figure 4a) was mainly due to the compressive volumetric strains accumulated during the initial cycles which caused an increment in the degree of saturation under the constant water content condition. The equalised suction reading was observed after the material attained a resilient state. It can also be observed that the reduction in suction during cyclic loading is significant from 490 kPa to 432 kPa for the sample (1D) initially dried to a water content of 6.16% before testing compared to the reduction in suction from 26 kPa to 21 kPa for the as-compacted sample (denoted by As in Figure 4a). This is mainly due to the water retention state of the sample where the sample close the main drying curve at high suction levels shows higher reductions of suction following a scanning water retention curve, compared to the sample at low suction levels that follows the main wetting curve (Kumar et al. 2022a). Furthermore, the higher suction value the higher the resilient modulus of the sample, as can be observed in Figure 4b. The resilient modulus of the sample with the suction equalised at 432 kPa was measured to be 79 MPa while the sample having a suction equalised at 21 kPa was found to be 58 MPa.

It can be observed that the sample having a water content of 6.16% shows a reduction in the M_R with the increment in repetitive loading cycles which is mainly due to loss of suction during cyclic loading. However, the sample having a water content of 10.8% shows an increment in the resilient modulus with progressive cyclic loading which is mainly due to dominant effect of densification of soil due to accumulations of the compressive volumetric strains during repeated cyclic loading while the decrease in the suction was small.

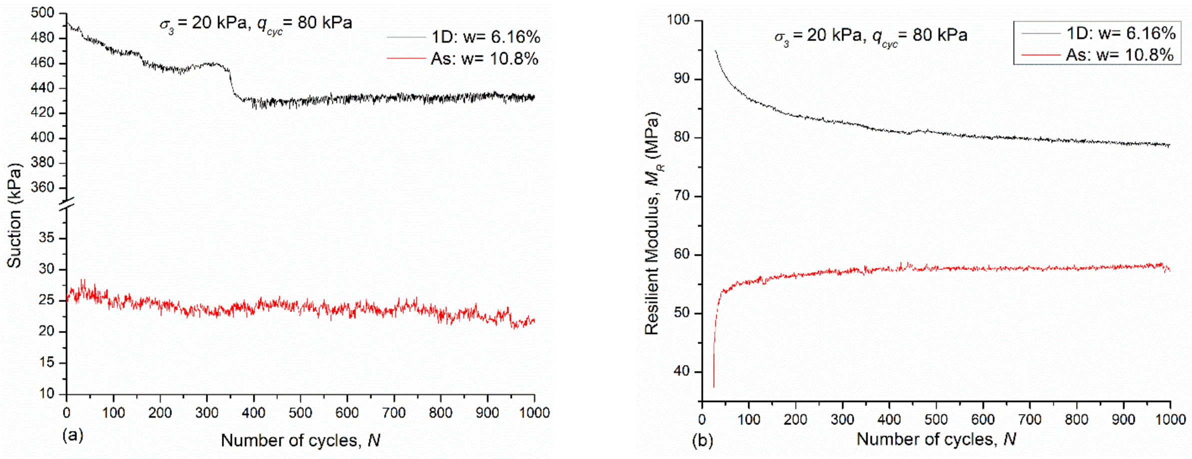

Figure 4: Results of changes with number of cycles (a) suction (b) resilient modulus.

a. Axial strain

Figure 5a shows the variation of the accumulated axial strain ε_a (sum of the axial recoverable and permanent strains) with respect to the cyclic deviatoric stress. It can be observed that ε_a increases with an increment in q_{cyc} for the lower suction *s* value since changes in *s* is small as it increased from 17 kPa to 25 kPa. This was also the case when the strains of samples with *s* of 378 kPa and 320 kPa are compared. However, in the case of a higher value of suction (433 kPa) a prominent impact on reducing the accumulated strain can be observed from 1.09% to 0.48% when q_{cyc} was increased from 60 kPa to 80 kPa implying the increase in the suction reduced ε_a accumulation. Figure 5b shows the variation of suction and the accumulated stain with respect to the confining pressure for the test conducted at q_{cyc} of 40 kPa. The reduction in the suction at the same σ_3 of 40 kPa led to an increment in ε_a due to loss of suction within the soil mass. However, the increment in σ_3 from 40 kPa to 100 kPa dominates the effect of reducing suction from 393 kPa to 302 kPa and 229 kPa leading to a reduction in ε_a.

b. Resilient modulus

Figure 6 shows the variation of resilient modulus with cyclic deviatoric stress q_{cyc} and confining pressure σ_3. Figure 6a shows that M_R reduced with the combined effect of the increase in the cyclic deviator stress from 40 kPa to 60 kPa and the decrease in the suction from 378 kPa to 320 kPa. This reduction trend was also observed when q_{cyc} increased to 80 kPa although the suction increase to 433 kPa implying that the effect of the increase q_{cyc} on the resilient modulus was greater than the effect of the suction values of the tested samples.

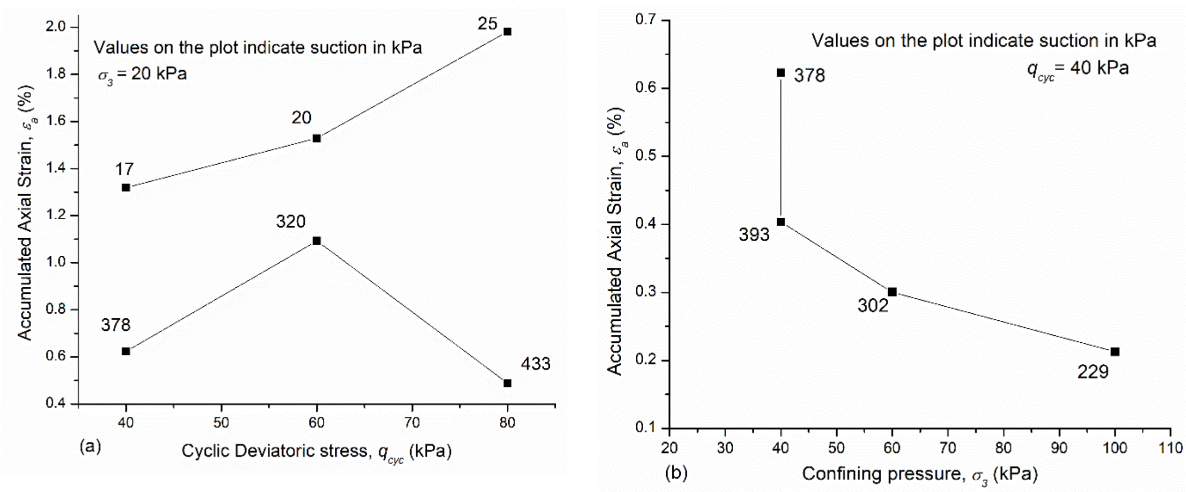

Figure 5: Variation of Accumulated axial strain vs. (a) cyclic deviatoric stress (b) confining pressure

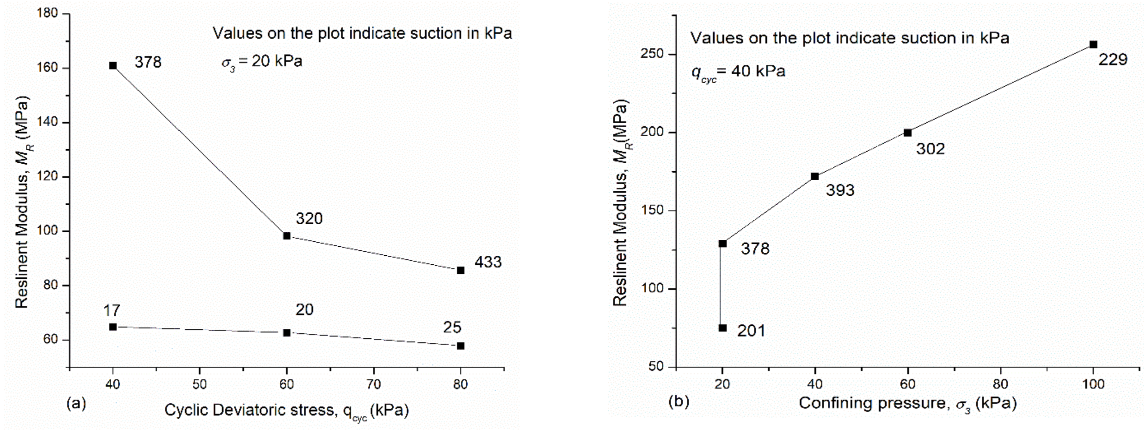

Figure 6: Variation of resilient modulus with (a) cyclic deviatoric stress (b) confining pressure.

It can be observed that that resilient modulus is dependent on suction level at a constant σ_3 of 20 kPa (Figure 6b) where M_R increased from 75 MPa to 129 MPa (72% increment) when suction increased from 201 kPa to 378 kPa. However, the increment in the confining pressure from 20 kPa to 100 kPa has a dominant impact on the increase in the value of M_R even though the suction value decreased from 378 to 229 kPa.

c. Accumulated axial strain and resilient modulus in terms of Bishop's stress ratio

In order to study the combined effect of the confining pressure, cyclic deviator stress and suction on the behaviour of the soil tested in this study, we introduced a Bishop's stress ratio as the ratio between the maximum cyclic stress q_{max} (sum of the cyclic deviator stress and resting stress) and the mean Bishop's stress:

$$\eta^* = \frac{q_{max}}{P^*} \quad (1)$$

where the Bishop's stress is obtained by:

$$P^* = P_{net} + S_r s \quad (1a)$$

where $P_{net} = (\sigma_1 + 2\sigma_3)/3$ is the mean net stress (the difference of total stress and pore-air pressure) and $S_r s$ is the suction stress. q_{max} is summation of cyclic deviator stress and resting stress.

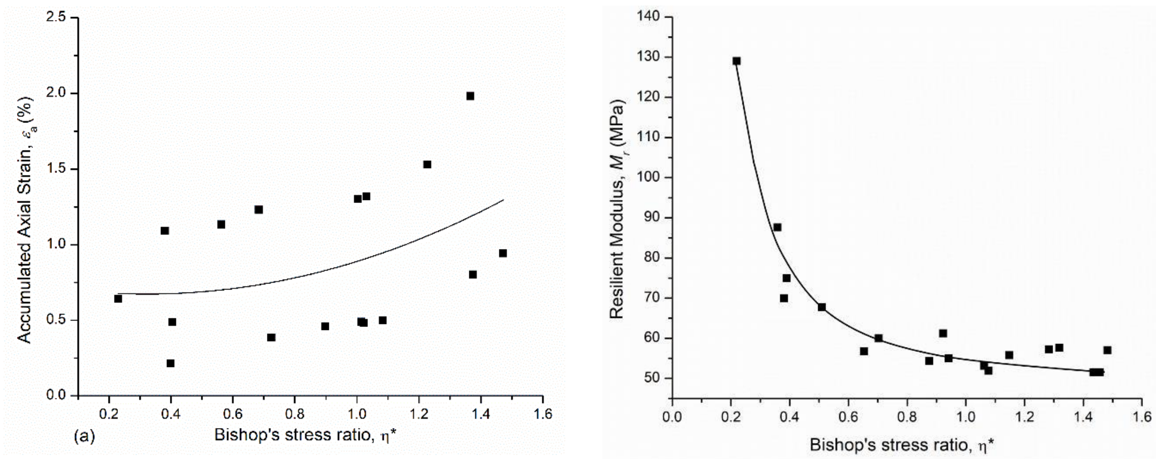

Figure 7: Variation of (a) accumulated axial strain (b) resilient modulus with Bishop's stress ratio

Although the data points of the accumulated axial strain shown in terms of the Bishop's stress ratio are relatively scattered, the results indicate an increment in ε_a with an increment in the Bishop's stress ratio. This can be due to the effect of the increment in the applied q_{cyc} or decrement in the mean Bishop's stress induced by suction reductions (Figure 7a). Azizi et al. (2021) showed that the effect of suction on the evolution of the accumulated axial strains cannot be precisely predicted by Bishop's stress and an additional parameter is required, i.e. a bonding parameter accounting for the effect of suction bonding between soil particles. However, Figure 7b shows a clear non-linear reduction in resilient modulus with an increment in Bishop's stress ratio. This can be due to the increase in the cyclic deviatoric stress or decrease in the mean Bishop's stress due to the decrease in the suction level. In both cases, the stiffness of the soil reduces leading to lower values of resilient modulus. However, the rate of the decrease in M_R reduces at higher value of the Bishop's stress ratio.

7. Conclusions

This paper presents an insight into the importance of direct suction measurement to investigate the cyclic response of unsaturated soils and its application to predict the accumulated strains and resilient modulus and hence the effect of changing water content levels on the formations of roads and railways. The cyclic triaxial setup was modified to allow a tensiometer to be used to directly measure suction on the mid-height of the sample and on-sample instrumentation was used to monitor volume changes. The setup enabled direct and quick measurement of suction within the shearing zone under atmospheric conditions which are not possible using other testing techniques such as the axis translation approach. The obtained results indicated that the accumulated axial strain was dependent on and decreased with the increase in the level of suction and confining pressure but increased with an increment in the cyclic deviatoric stress. The resilient modulus showed dependency on the level of soil suction where the resilient modulus increased with an increment in the soil suction as well as the confining pressure while it decreased with an increment in cyclic deviatoric stress. The obtained data showed that the accumulated axial strain increases with the Bishop's stress ratio while the resilient modulus showed a non-linear decrement with an increment in the Bishop's stress ratio. The obtained results indicated that the on-sample measurements provide a reliable measurement of suction during the cyclic triaxial testing that can be used for the interpretation of the behaviour of unsaturated soils subjected to repetitive cyclic loading.

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