The Use of High-Capacity Tensiometer for Cyclic Triaxial Testing of Railway Formation material

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Abstract. The formation layers of railway embankments are often unsaturated and subjected to coupled cyclic traffic-induced and hydraulic loading. Understanding this coupled response requires the development of a testing protocol capable of subjecting soil samples to cyclic loading while continuously monitoring soil water retention properties. An accurate measurement of the suction evolution within the soil during repeated cyclic loading is crucial for interpreting the response of the soil considering the principles of unsaturated soil mechanics that are commonly neglected during the design of this infrastructure. In this paper, we present the use of a high-capacity tensiometer of capacity 2 MPa and resolution 0.5 kPa developed at Durham University, capable of measuring pore-water pressure in both positive and negative ranges (suction) on the body of soil samples. The setup allowed continuous monitoring of suction at the mid-height of the unsaturated soil sample during cyclic triaxial testing while continuously measuring the volumetric deformations with the help of on-sample displacement transducers. The obtained results in terms of permanent strain and resilient modulus were dependent on the evolution of suction stress during cyclic loading. The obtained results were then interpreted in terms of Bishop's stress where the permanent strain was consistently found to decrease with an increase in the Bishop's stress. The resilient modulus was also found to be correlated to Bishop's stress ratio.

Keywords: suction, subgrade soils, unsaturated soils, tensiometer, railways.

1 Introduction

Unsaturated compacted soils present within the embankment of roads and railway formations are subjected to coupled cyclic traffic-induced loads and hydraulic loading cycles (Azizi et al., 2022; 2023). This coupling behaviour needs to be fully understood by the means of a testing procedure that can subject soil samples to cyclic loading while consistently observing their water retention characteristics. (Kumar et al., 2022).

A conventional cyclic triaxial testing apparatus is commonly employed to study the cyclic behaviour of compacted soils. While many studies have focused on understanding the cyclic response of formation soils under saturated conditions (Shahu et al., 1999), it is important to note that soils within railway embankments typically remain unsaturated throughout their operational life as they lie above the groundwater table. Therefore, assessing the cyclic response of these unsaturated soils specifically in terms of cumulative plastic deformations (permanent deformation in excess of recoverable deformation) and resilient modulus (the ratio of cyclic deviatoric stress to recoverable strain) becomes crucial within the framework of unsaturated soil mechanics. Moreover, the evident impact of climate change marked by frequent rainfall and drought continuously imparts hydraulic loading and alters the water content and suction levels within these soils, influencing their long-term performance (Brown, 1996). The fluctuation in water content coupled with the dynamics of traffic can exacerbate cumulative deformation and resilience of subgrade soils leading to premature failure (Blackmore et al., 2020). Precisely determining the water retention properties followed by soil under repeated cyclic loading is essential for interpreting the behaviour of these unsaturated soils, which is overlooked during the design of this infrastructure.

In recent times, there has been an increasing use of modified cyclic triaxial testing systems while incorporating various instruments such as psychrometers, suction probes and axis-translation techniques, to measure or control soil suction during cyclic tests. This is essential for obtaining reliable results regarding the variation of the strain and resilient modulus of soil with changes in suction (Sivakumar et al., 2013). However, these modified triaxial testing systems come with drawbacks, as they are expensive, cumbersome, and require the expertise of trained professionals to conduct the tests. Furthermore, it does not monitor suction changes at the mid-height of the sample that is near the shearing zone where maximum volumetric deformation takes place, instead, measurements are done away from non-uniform stress conditions at the specimen ends which could influence the accuracy of the measurements.

Moreover, achieving water equilibrium conditions for each applied suction value especially in the case of fine-grained unsaturated soils using suction-controlled techniques, such as the axis-translation technique, typically requires a relatively long testing time. It is worth noting that axis-translation approach does not align with actual field conditions, where air pressures are atmospheric and water pressures are negative (Toll et al., 2013). Additionally, the low permeability of the ceramic porous stone used in axis translation leads to a delayed response in pore water pressure measurements. Therefore, measuring water pressure at the end of the sample may not accurately represent suction along the height of the specimen during loading cycles because of delayed suction equilibration.

The introduction of high-capacity tensiometers for measuring suction within soils under natural conditions has brought about a paradigm shift in understanding and explaining the behaviour of unsaturated soils (Toll et al., 2013). This is primarily attributed to the faster response time, direct suction measurement and easy maneuverability of tensiometers due to their miniature size. Obtaining readings using tensiometers takes seconds to minutes compared to days required by axis-translation. It is to be pointed out that using tensiometers have become common in monotonic triaxial testing (Solan et al. 2019). However, the measurement of suction using a high-capacity tensiometer during cyclic triaxial testing has yet to be given proper credence.

This paper describes the use of a high-capacity tensiometer during cyclic triaxial testing of a clayey sand where suction was directly measured at the sample's mid-height. Additionally, on-sample displacement transducers were used to measure volume changes during the different stages of testing. This testing protocol allowed the interpretation of the dynamic hydro-mechanical behaviour of the samples during the cyclic deviatoric loading. The obtained results are then reported in terms of accumulated strain, suction and resilient modulus of the soil.

2 Material description and sample preparation

The soil recovered from the subgrade layer of a 650 km heavy-haul coal line railway embankment was clayey sand. The embankment was constructed along the southeastern coast of South Africa. The South African Transnet S410 specification of railway earthworks describes the material as class B subgrade (400 mm thick) laid below the sub-ballast layer. The recovered soil was transported to the UK with logistic support from the University of Pretoria, South Africa and tested in the geotechnical engineering laboratory of Durham University, United Kingdom. The soil contained 79% sand, 12% silt, 9% clay. The soil has a liquid limit of 25, a plastic limit of 16 and a plasticity index of 9.

The soil underwent a 24-h oven-drying and followed by mechanical grinding using wooden mallet for obtaining 2 mm sieve passed samples. A water content of 10.8% (slightly on the wet side of optimum) was then added to the soil. The sample was then sealed in a plastic case for 24 hours to achieve water homogenization. The wet soil was dynamically compacted in a compaction mould (height 200 mm and diameter 100 mm) following the standard Proctor test procedure (BSI 1990). The sample of diameter 70 mm and height 140 mm was then recovered from the compaction mould where an average density of 1.84 Mg/m^3 and average water content of 10.8% was achieved. It is to be noted that we compacted the samples on the wet of the optimum. This ascertained the suction level of the samples lies within the measurement range of the tensiometer. It should be noted that even a small reduction in the water content can show a very large suction value that might cross the measurement range of the tensiometer.

Prior to testing, specimens used for unsaturated testing were subjected to air-drying. Air-drying was carried out in a laboratory environment by exposing the sample to a constant room temperature of 20°C (±0.5°C) and relative humidity of 34%. The air-dried soil was wetted by keeping the sample in a closed chamber at a high relative humidity close to 100% to mimic the field condition of water infiltration during rainfall. The weight and dimensions of the specimen were monitored at a definite interval to track the changes in the water content and the volume. The sample was relatively dense so no disturbance was observed during this process. 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 in a plastic bag for 24 h. These processes helped in obtaining the different values of suction and water content under varying hydraulic loading conditions. The specimens were then mounted on a triaxial base pedestal. Thereafter, the suction of the sample was monitored using the tensiometer. We assumed that a constant suction reading indicated the condition of water homogenization within the sample.

3 Experimental Methodology

The testing programme involved the repeated load test on unsaturated soil specimens by using a GDS double-cell wall dynamic triaxial apparatus as shown in Figure 1. The equipment comprises a load frame with a 10 kN capacity equipped with a dynamic actuator, a double amplitude displacement of capacity 20 mm. The operational frequency range of the actuator spans from 0.1 to 5 Hz. The volume changes and suction were monitored by employing on-sample instrumentation. Local measurement of axial and radial deformations was performed using the submersible Linear Variable Differential Transformers (LVDTs) mounted on the sample with a rapid hardening glue to keep the LVDTs in the position (Figure 1). The measurement of suction was performed by the commercial tensiometer developed at Durham University capable of measuring suction to a range of 0-2 MPa and having a resolution of ± 0.5 kPa, suitable for measuring small pore water pressure variations (Toll et al. 2013). The calibration of tensiometer was carried out as per Lourenço et al., 2008.

An access hole was cut on the latex membrane to allow for intimate contact of the tensiometer with soil. A rubber groumet was used over the tensiometer casing 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 the uniform and the intact sealing. Figure 1 shows a photograph of the GDS triaxial apparatus and a sample with on-sample instrumentation on a sample of diameter 70 mm and height 140 mm used in this study. Further details about the installation of on-sample instruments are mentioned in Kumar et al., (2022 a,b).

Fig. 1. Photograph of GDS triaxial testing apparatus and on-sample instrumentations

4 Cyclic testing and suction monitoring

Figure 2 (a&b) shows the typical cycles of deviatoric stress q_{cyc} of 40 kPa applied and the induced accumulated and resilient strains. This stress condition represented the actual field condition of stress at the subgrade level during the passage of a heavy haul freight train (26 t/axle) at a speed of 50-80 km/h. A resting stress $q_{resting}$ of 10 kPa was maintained throughout the cyclic loading to incorporate the dead load from the rail and the ballast. The total number of repetitive loading cycles applied was 1000 with a loading frequency of 1 Hz. This which was sufficient to bring the resilient response of the soil sample indicated by the evolution of only recoverable strains while changes in permanent strains became negligible. The loading frequency of 1 Hz simulated the average train speed for a wagon of length 9.702 m at the subgrade level.

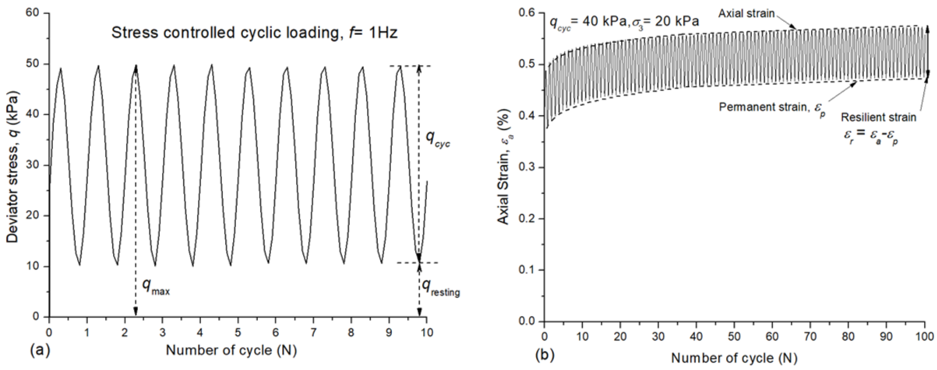

Fig. 2. Typical loading and strain with respect to cyclic loading (a) deviatoric stress variation (b) axial strain

The measured suction for one of the specimens during assembly, isotropic compression and cyclic deviatoric loading is shown in Figure 3a. After the tensiometer was mounted, it can be seen that suction within the sample started from zero to attain an equalized suction reading of 32 kPa. The elapsed time required for suction equalisation was high because soil paste was used at the porous stone of the tensiometer to ensure good contact between the soil and the 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. Once suction equilibration was achieved among the tensiometer porous stone, soil paste, and soil samples, any fluctuation in suction within the sample would lead to quick response in the tensiometer reading.

Figure 3b shows the results of changes in the soil suction during the application of confining pressures of 40 and 60 kPa. It shows a quick reduction in the suction value from 450 kPa to 410 kPa for confining pressure of 40 kPa. This was followed by a gentle increase in suction to 430 kPa with the progressing of time and attained an equalized state. Such local change in suction disappeared as the water became homogenised across the specimen. During compression, the suction reduced due to the volumetric compression that caused an increase in the degree of saturation S_r under the constant water content condition. The cyclic loading was applied once an equa ized suction reading was observed. Such trend in suction variation was not the case for deviatoric loading stage. It is to be noted that the suction value was stablished after the attainment of the stable resilient state of the sample (discussed in the following section).

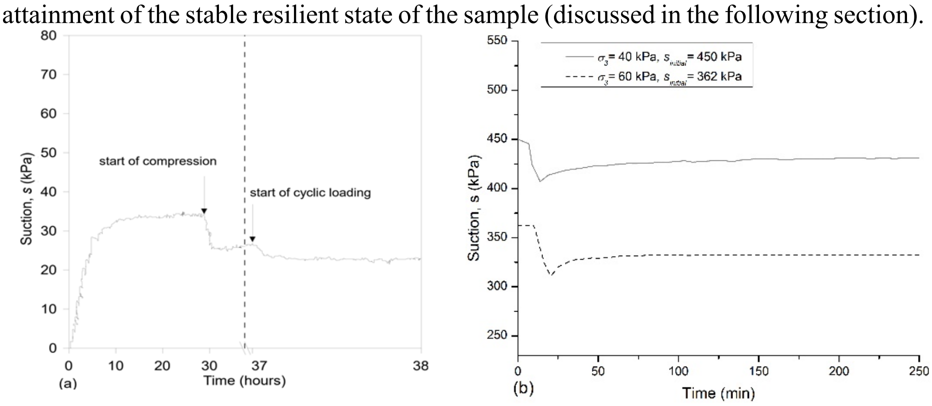

Fig. 3. Suction readings (a) under different stages of cyclic triaxial testing (b) isotropic compression

5 Results and discussions

5.1 Dynamic hydro-mechanical behaviour

Figure 4a shows the results of the variation of suction for the test conducted under confining pressure σ_3 of 20 kPa and cyclic deviator stress q_{cyc} of 40 kPa for the sample tested at water content of 8.13% and initial suction value of 60 kPa. The suction reduction from 45 kPa to 39 kPa and then equalisation were observed. This is mainly due to the compressive volumetric strains accumulated during the initial cycles which caused an increment in the degree of saturation. The equalised suction reading was observed after the material attained a resilient state.

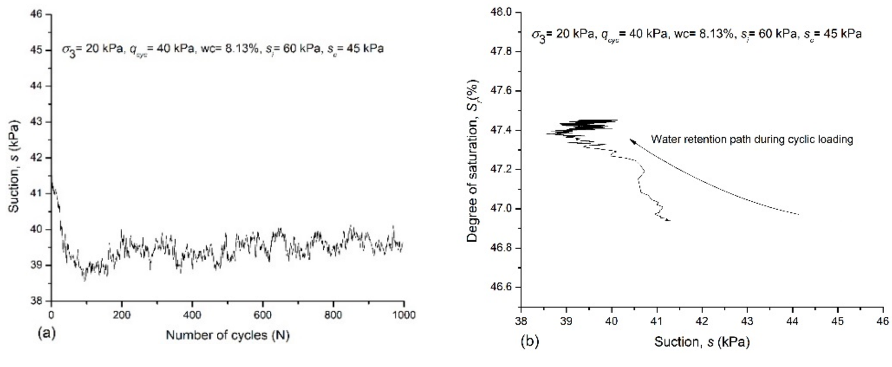

Fig. 4. Suction variation: (a) suction reduction with number of cycles (b) dynamic water retention path for a sample tested at q_{cyc} of 40 kPa

Figure 4b shows the dynamic water retention path traced by the sample during cyclic loading. It can be observed that the sample moved along the wetting path due to the development of compressive volumetric strain under the constant water condition causing an increment in the degree of saturation and reduction in suction. This is mainly because the reduction in suction facilitated the plastic slippage at the particle contact up to the point of attainment of a stable resilient state.

5.2 Permanent strain and resilient modulus

The on-sample instrumentation provided crucial information on the dynamic changes in the suction and degree of saturation. Mean Bishop's stress was then used to interpret the soil cyclic behaviour. Bishop's stress $p^{*}= p_{net} + S_r s$ where $p_{net} = (\sigma_1+2\sigma_3)/3$ is the mean net stress and $S_r s$ is the suction stress. Figure 5a shows variation of accumulated plastic strain measured after 1000 cycles with Bishop's stress ratio η^* (ratio between q_{max} and p^*). It can be observed that the plastic strain increased non-linearly with an increment in η^*. This is mainly because increase in q_{cyc} facilitated the particle slippage at their contacts.

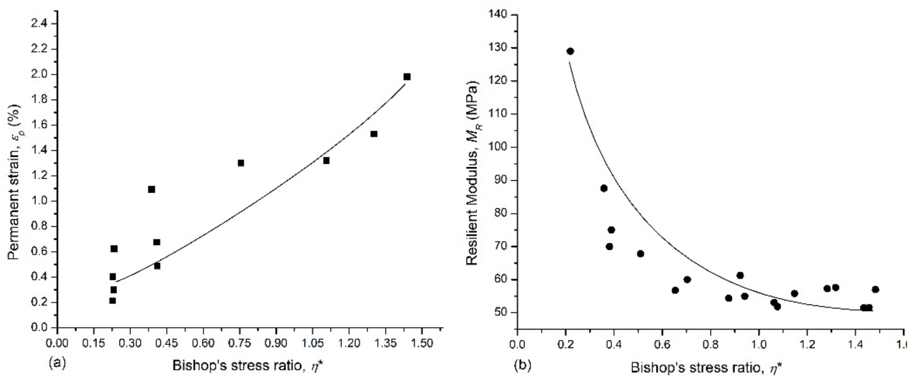

Fig. 5. Results in terms of (a) permanent strain (b) Resilient strain (some of the data adopted and redrawn from Kumar et al. 2023)

Figure 5b shows a non-linear reduction in M_R with an increment in η^* as the ratio between the maximum cyclic stress and the mean Bishop's stress. This is because an increase in the cyclic deviatoric stress or a decrease in the mean Bishop's stress due to the decrease in the suction level. In both cases, the stiffness of the soil was reduced leading to lower values of resilient modulus.

6 Conclusions

This paper presents the importance of using high-capacity tensiometer to investigate the cyclic response of unsaturated formation soils and its application to predict the strains and resilient modulus for railway formation material. The setup allowed the direct and quick measurement of suction under atmospheric conditions at the zone of maximum shearing. The obtained results helped in predicting dynamic water retention path traced by the sample during the cyclic deviatoric loading. Furthermore, an accurate estimation of suction and sample deformation helped in representing the sample deformation and resilient modulus in terms of Mean Bishop's stress. Therefore, it can be stated that 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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