The influence of cyclic loading frequency on the response of an unsaturated railway formation soil

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ABSTRACT

This paper presents the results of cyclic triaxial tests conducted on unsaturated soil samples recovered from the railway embankment of a South African coal line to investigate the influence of cyclic loading frequency on a formation layer material, in this case a clayey sand. The testing involved suction-monitored repeated loading tests accounting for the conditions likely to be encountered in practice under varying train speed. The results of single-stage loading tests with a frequency applied individually in a range of 0.5-4 Hz were compared to the results of multistage loading tests with a frequency increasing from 1 to 4 Hz. The results of the single-stage loading tests indicated that the accumulated axial strain increased with an increase in the cyclic frequency, implying that a higher train speed would result in a higher level of the permanent deformation. The staged increase in the frequency of the multistage loading tests showed that the permanent deformation mainly took place during the first packet of cyclic loads whereas the deformations measured during the following repeated loads were negligible. Suction reduction and an increase in degree of saturation during cyclic loading was dependent on the water-retention state of the sample. The results were then interpreted in terms of resilient modulus.

INTRODUCTION

In recent years, the rapid urbanization and increasing population have put enormous pressure on the existing railway infrastructure requiring the adoption of heavier, faster, and frequent traffic on the trackbed that comprise compacted soils. These soils commonly lie above the groundwater table and remain unsaturated and are affected by water content and suction variation (Brown 1996). Besides, with a growing demand for higher train speeds, an increasing amount of traffic, and heavier axle loads of trains, a higher dynamic load is exerted on the track substructure (Li and

Selig 1996). Hence, the track substructure should be designed to cater for the damaging effect of dynamic railway traffic while incorporating the impact of environmental loading (soil-water retention characteristics) so that vehicle operating cost, passenger safety, and comfort could be ascertained during the service life. The problem of continuous and costly maintenance of track structure remains unsolved due to the inability of the present design protocols that rely mostly on the empirical methods (Drumm et al. 1990). Gräbe (2002) presented the case study of changing traffic frequency over the Richards bay coal line in South Africa from 20 t/axle to 26 t/axle where 70% of the total maintenance cost was associated with the repair of the failed track foundation. Burrow et al. (2007) reported the condition of trackbeds for various sites in the UK and highlighted the requirement of frequent maintenance considering the changing traffic and climate conditions. Such performance was mainly due to the change in the soil suction brought by water fluctuation together with the cyclic traffic loads. Therefore, there is a need to develop a design philosophy that can incorporate the influence of a higher train speed, traffic frequency with changing train speed, and heavier axle loads while incorporating soil-water retention properties.

Several researchers have performed cyclic triaxial testing to understand the influence of dynamic stress and confining pressure on the development of permanent strains and resilient modulus (a ratio of dynamic stress and recoverable strains) while soil samples were prepared at different water content and suction levels and tested at a constant cyclic frequency (Shivakumar et al. 2013; Blackmore et al. 2019). The suction values in these tests were either controlled or measured indirectly. Liu and Xiao (2010) performed cyclic triaxial testing to study the effect of deviator stress, cyclic frequency and water content on the accumulation of strains and resilient modulus at an individual frequency of 1 Hz and 2 Hz and reported the importance of cyclic frequency in the permanent strain accumulation and the resilient modulus. Schulz-Poblete et al. (2019) performed laboratory-scale physical model testing on the trackbed infrastructure by applying multi-stage cyclic frequency loading while keeping the dynamic stress constant. The authors reported the importance of strain accumulation during the first stage of loading. However, the studies reported in the literature have not shown the comparison of individual frequency loading (a case of the traffic condition with a constant speed) and multi-stage loading frequency (a case of traffic condition with an increasing speed) on the accumulation of strains and resilient modulus. Also, the evolution of suction values during the different stages of the testing was not directly measured in the reported study nor was it integrated with the changes in the degree of saturation (soil-water retention characteristics).

The research reported in this paper investigates the behaviour of clayey sand subjected to cyclic deviator stress where the frequency of the deviator stress was applied individually and at multi-stages in packets of 1000 cycles at a constant confining pressure. Direct measurement of suction during the different stages of testing was carried out by installing a tensiometer at the mid-height of the sample close to the zone of maximum shearing. The changes in the degree of saturation were obtained by monitoring volume changes of samples by means of continuous measurement of axial and radial deformations using on-sample displacement transducers. The obtained results are discussed in terms of strain accumulation, suction and degree of saturation, and resilient modulus of the soil.

SAMPLE PREPARATION

The material tested was collected from the 650 km long heavy-haul South African Coal export line that links around 40 mines located at the Mpumalanga coalfields to Richards Bay Coal Terminal (RBCT). The track embankment comprises four 200 mm thick layers below the ballast i.e. special sub-ballast, sub-ballast, class A and class B subgrades, defined by South African Transnet S410 specification for railway earthworks (Gräbe 2002; Gräbe and Clayton 2009). This paper describes the testing conducted on the Class B subgrade material, which is sand containing 6 % clay. The material was oven-dried, and then mechanically ground, and the particles passing through a 2 mm sieve were collected for sample preparation. For each specimen, ground soil was mixed with the target water content i.e. 10.8% (wet side of optimum, OMC= 10.2% and MDD= 1.871 Mg/m^3) and sealed in a plastic case for 24 hours to allow for water equilibration. The soil was then placed in a Proctor mould and dynamically compacted using the 2.5 kg standard proctor rammer in four layers. The cylindrical specimen was then extruded to 70 mm diameter and 140 mm height.

EXPERIMENTAL METHODOLOGY

Stress-controlled cyclic triaxial testing was carried out using a double cell wall cyclic triaxial apparatus capable of applying repetitive cyclic loading to 5 Hz frequency. The deformations and suction during the testing were monitored by employing on-sample instruments. Local measurement of axial and radial deformations was carried out using submersible Linear Variable Differential Transformers (LVDTs) with a, resolution of 0.1 µm. Two axial LVDTs were mounted on the radially opposite sides of the sample and a radial LVDT was mounted across the middle of the sample, using a radial strain belt as shown in the inset in Figure 1.

Direct measurement of suction was performed using a high capacity tensiometer developed at Durham University capable of measuring suction to a range of 2000 kPa (Toll et al. 2013; Liu et al. 2020; Azizi et al. 2020). Figure 1 shows the cyclic triaxial setup used for testing and the sample with on-sample instruments. During sample assembly, a rubber membrane was fitted over the sample and a top cap was placed to preserve the water content of the sample. Before tensiometer installation, wet soil paste was applied over the sensing face of the tensiometer which acted as an interface between the tensiometer and the soil sample. The constant suction value after mounting the tensiometer confirmed the attainment of water equilibration. Thereafter, the deformation sensors were installed. Figure 2(a) shows the equalisation of suction reading after tensiometer assembly where suction equilibration was achieved within 40 h of sample arrangement. More details of the experimental methodology can be seen in Kumar et al. 2021 and Azizi et al. 2021. After the establishment of suction equilibrium, a constant confining pressure σ_3 of 20 kPa was applied as the railbed material normally operates at shallow depths having a low overburden pressure.

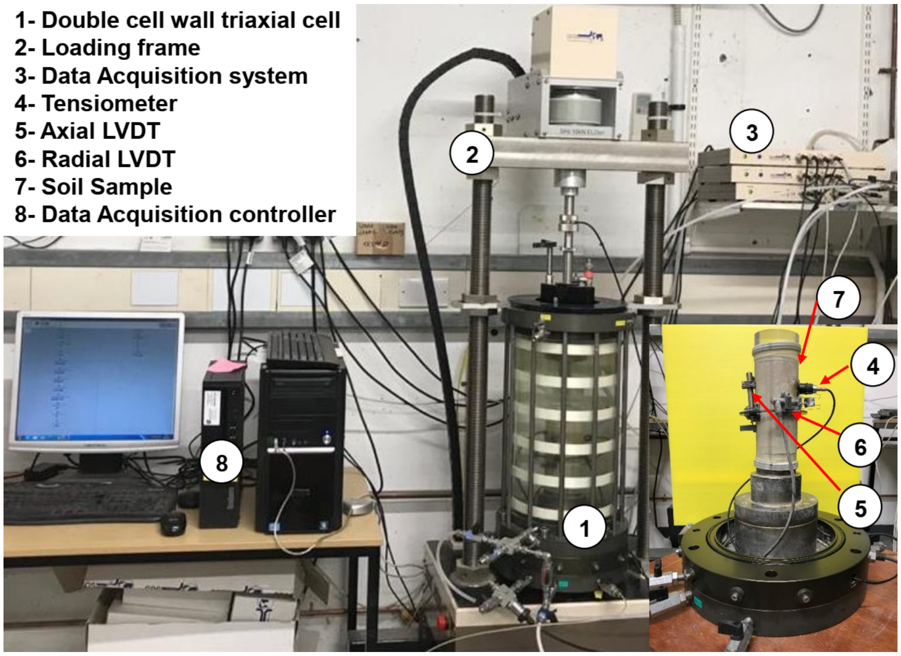

Figure 1. View of triaxial setup and on-sample instrumentations

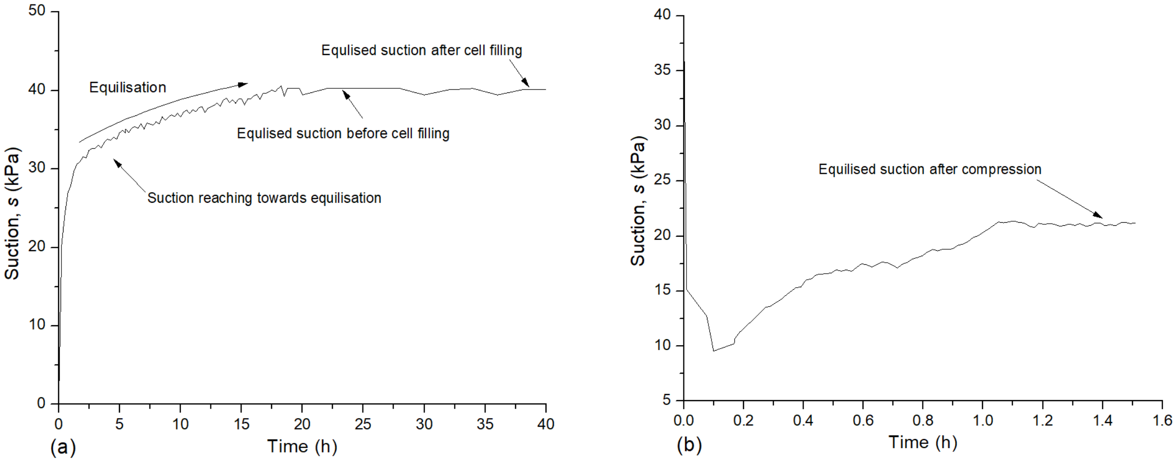

Figure 2. Suction reading: (a) during equalisation and cell filling (b) during compression

Figure 2(b) shows suction reading during compression where a quick reduction in the suction value is observed followed by a gentle increase with the elapsed time before reaching an equalized stage. The decrease in suction is due to an increase in the degree of saturation due to isotropic compression. However, an initial reduction in suction is slightly greater than might be expected because of local pressurization of the wet soil paste used to make contact between the sensing face of the tensiometer and the soil sample. This small local effect disappeared as the water becomes homogenised across the specimen. This trend in suction changes was not observed during cyclic loading as the confining pressure was maintained constant. Cyclic deviator stress q_{cyc} representative of the movement of the train axle loads was applied after the attainment of suction equilibration. The South African coal line carries a maximum axle load of 26 t/axle which applies 50 kPa of vertical effective stress at the base of sub-ballast (Gräbe and Clayton 2009). In the present study, q_{cyc} of 40 kPa was applied while 10 kPa of resting stress was maintained during the cycles (Figure 3). This allowed the loading piston ram to remain in continuous contact during the cycles and also considering the weight of track superstructure i.e. rails, sleeper and ballast on the subgrade soil. The number of cyclic load cycles imposed during each test was 1000 which was sufficient to bring the specimen to a stable resilient state.

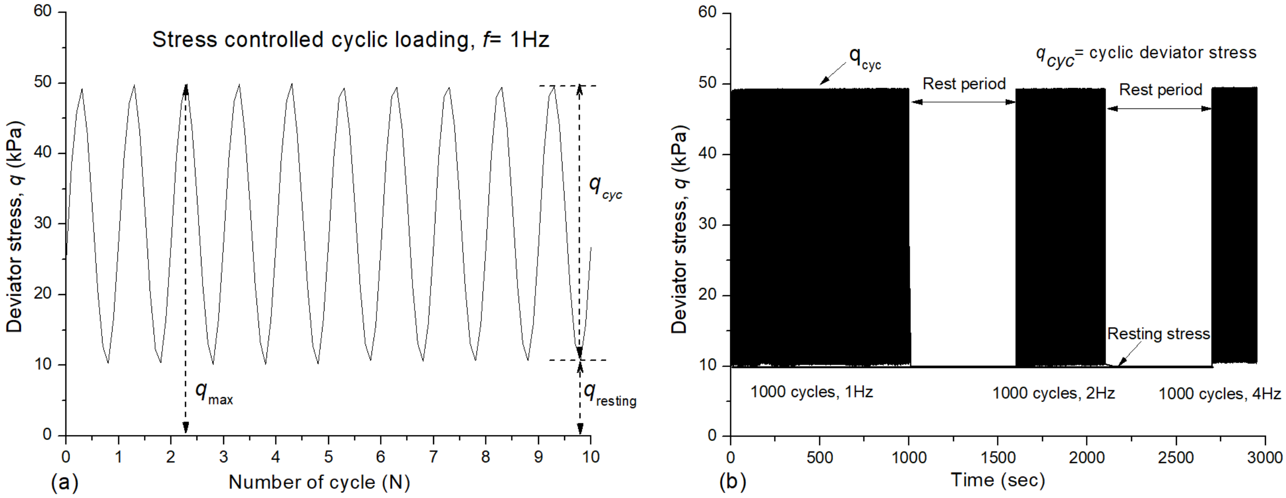

Figure 3. Typical loading: (a) individual loading (b) multi-stage loading

Cyclic load frequency affects the cumulative plastic deformation and resilient modulus of soils which is dependent on train speed, carriage length and axle distance. In order to represent the case of different traffic frequencies ranging from the movement of trains with constant speeds and successive passing of trains with a changing speed, individual and multi-stage loadings were applied by varying the frequency of loading. The undesirable strain accumulation and resulting serviceability failure in the railbed may occur when the train speed increases beyond the serviceable speed or if trains with different speeds pass in a short time interval. For the case of soil subgrade, one load cycle is sufficient to represent four axles under two adjacent train bogeys (Liu and Xiao 2010). The bogey passing frequency f is calculated as $f=v/l$, where v is the train speed in km/h and l is the bogey length in m. A typical wagon length running on the heavy haul track in South Africa is 9.702 m (Gräbe 2002). Frequency variation from 0.5, 1, 2 and 4 Hz is equivalent to the train speed ranging from 17, 35, 70 and 140 km/h indicating a heavily restricted speed to a semi-high speed. The normal operating speed of South African Transnet rail is 50-80 km/h. Figure 3 provides the details of typical loading applied during the testing. Table 1 gives the details of the testing program.

Table 1 Details of the testing program

Test No.	Water content (%)	Dry density ρ_d (Mg/m^3)	Initial degree of saturation S_r (%)	Initial suction s (kPa)	Test Frequency f (Hz)
T1	10.40	1.839	64.54	47	0.5
T2	10.80	1.839	64.29	40	1, 2, 4
T3	7.21	1.880	46.24	420	1, 2, 4
T4	10.50	1.831	61.70	49	2
T5	10.78	1.841	64.60	42	4

RESULTS AND DISCUSSIONS

Strain accumulation

Figure 4 shows the accumulation of axial strain ε_a with respect to the elapsed time during loading cycles (1000) for samples subjected to individual and multistage frequencies. It has to be pointed out that the soil water content is almost the same for these tests i.e. 10.62±0.18%, hence the impact of suction on strain accumulation is not dominant. The cyclic behaviour of the tested soil showed that 1000 load cycles were sufficient to bring the specimen to a stable resilient state. It can be observed that the maximum strain accumulated during the initial cycles for all the tests and thereafter the rate of strain accumulation decreased while samples approached the stable resilient stage. This is mainly because initial loading cycles produced higher plastic strains and thereafter strain accumulation became limited indicating the attainment of a purely recoverable strain state. It can also be observed that strain accumulation at resilient stage is proportional to the frequency of loading cycles (Figure 4a) for the individual frequency loading where ε_a of 0.84% was obtained for f = 0.5 Hz and ε_a of 1.92% was obtained for f = 4 Hz indicating 56% increment (Figure 4a).

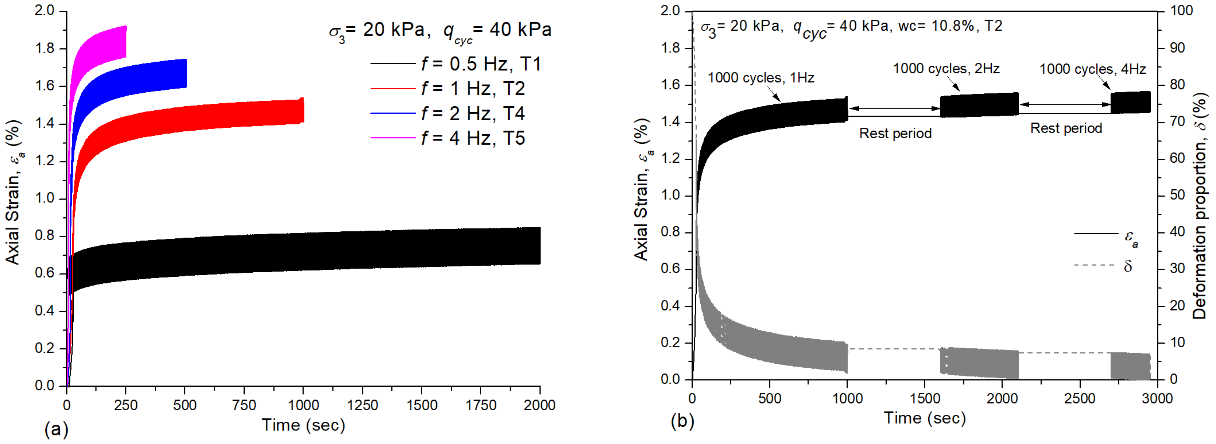

Figure 4. Axial strain variation: (a) individual frequency (b) multi-stage frequency

This shows that an increase in loading frequency would impart higher dynamic impact leading to a higher level of deformation accumulation. However, the results showed a non-linear increment in the strains when the individual loading frequency is changed from f = 0.5 Hz to f = 1 Hz (44% strain increment) and from f = 2 Hz to f = 4 Hz (9% strain increment). This indicated that the particle rearrangement is dependent on the frequency of the applied cyclic deviator stress where particles have sufficient time to deform during the application of loading at f = 0.5 Hz and 1 Hz. Whereas, the faster application of cyclic loading resembles a quick application and release of loading cycles and it was not sufficient to force the particle rearrangement as can be seen for f = 2 Hz and 4 Hz. The result of multistage loading frequency from 1-4 Hz indicated a maximum strain accumulation of 1.53% during the first packet of loading cycles (1 Hz) showing the maximum proportional deformation i.e. around 95% deformation accumulation (Figure 4b). A negligible deformation can be observed when f was increased from 2 to 4 Hz i.e. 2nd packet and 3rd packets of 1000 loading cycles. This is mainly because the strain accumulation during the multi-stage loading frequency is governed by the magnitude of q_{cyc} where maximum irrecoverable strain accumulation occurred initially (f= 1Hz) and even though frequency was increased to 4 Hz it did not lead to significant irrecoverable strains.

Suction and degree of saturation variation

Figure 5 shows the variation of suction s and degree of saturation S_r with respect to the elapsed time for samples subjected to individual frequencies of 1000 cycles. The initial suction reduction and then quick equalisation in the suction reading were observed for all the tests (Figure 5a). This quick equalisation of suction is mainly because of relatively high S_r of the soil i.e. around 65% that allowed quicker distribution of pore-water during the cyclic loading. The reduction in the void ratio with an increase in frequency of loading increased the degree of saturation of the soil sample as can be seen in Figure 5b. Although S_r changed from 65.4% to 67.5% for the sample tested at 10.8% for water content (f= 1 Hz), the suction change was only around 3 kPa.

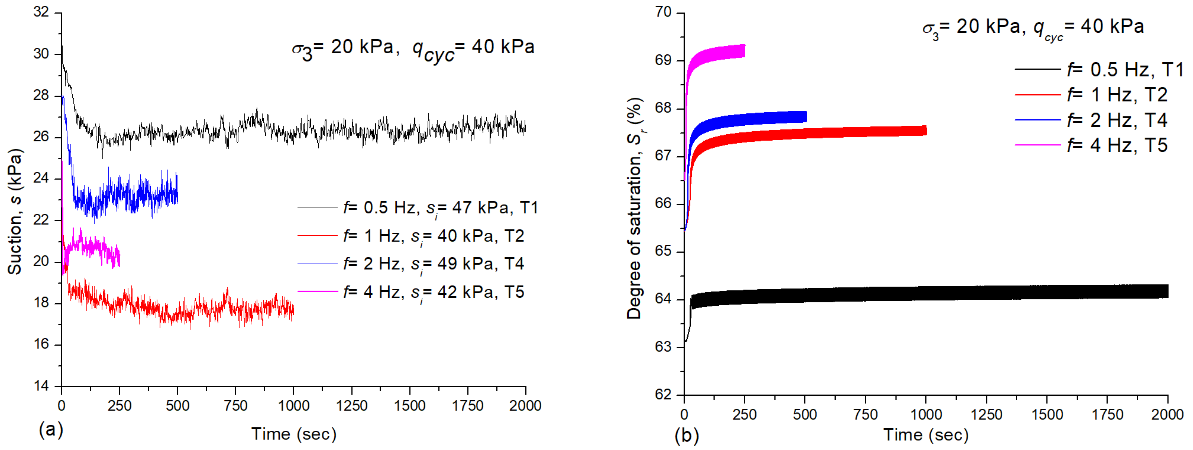

Figure 5. Individual frequency results: (a) suction variation (b) degree of saturation

Figure 6 shows the variation of S_r and s for the multi-stage loading frequency test where maximum changes can be observed for the initial loading frequency and a negligible variation was observed for the higher frequency range. This is mainly because of the negligible impact of $f = 2$ and 4 Hz application on increasing the strain accumulation thereby not affecting the development of S_r and evolution of s. This indicates that the sample cannot be further densified by only increasing f. The suction reduced and became stable after the application of the load cycles, this is because of the reduction in the void ratio of the soil during initial loading cycles and thereafter the changes in the plastic strain becomes negligible thereby making the suction stable.

It has to be pointed out that a very small change in the suction value was observed for all the samples tested on the wet side of the optimum. However, the sample tested on the dry side of optimum after being air-dried to 7.21% of water content and $s = 413$ kPa shows a suction reduction of 35 kPa even with a small increase in S_r from 47.12% to 47.8% (Figure 6a). This is because the suction reduction due to an increase in S_r is mainly dependent on the water-retention state of the soil sample where a sample lying on the drying path showed a higher suction reduction even with a gentle increase in S_r and on the contrary, a sample lying on the wet side of optimum showed a gentle reduction in suction even in the case of a marked increase in S_r. The equalisation of suction was delayed for the sample having the suction value of 413 kPa which is primarily because of lower permeability of the soil at a low level of degree of saturation leading to a delay in distribution of water (Figure 6a). This is also evident from Figure 6b where the water-retention paths traced by both the samples during the application of the packets of loading cycles are shown. The suction evolution is dependent on the equilisation of water and its water content as it can be seen that a sudden increase in S_r due to volumetric compression is not resulted in quick reduction in suction due to the delayed water equalisation for the sample having water content of 7.21% compared to the sample having $w = 10.8\%$.

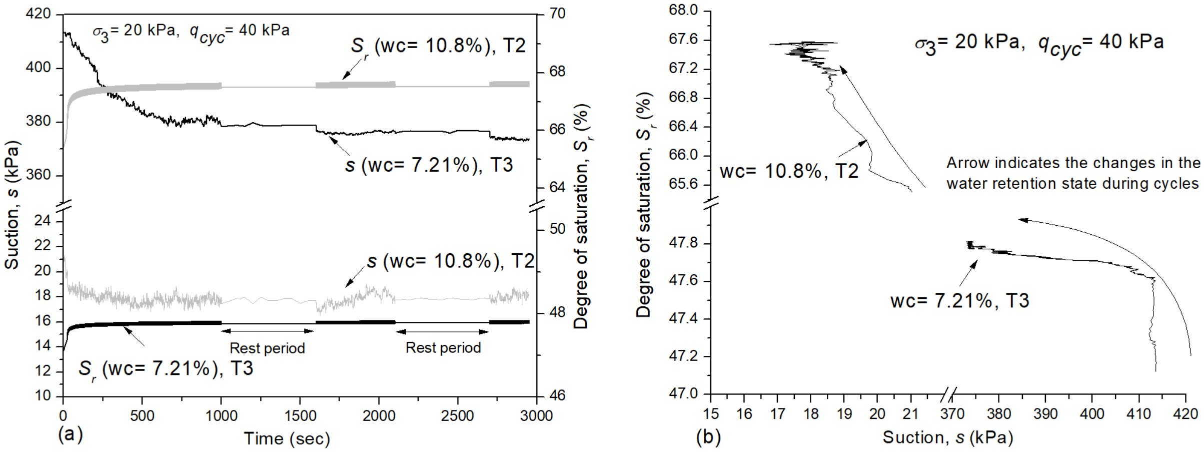

Figure 6. Multi-stage frequency tests: (a) suction and degree of saturation (b) Suction and degree of saturation variation

Resilient Modulus

Figure 7a shows the comparison of M_R for the loading frequency applied individually and at multi-stages. It can be observed that M_R reduced non-linearly from 56.5 MPa to 47.3 MPa during the application of individual f from 0.5 Hz to 4 Hz indicating the loss of soil resiliency when higher f was applied. This is because a higher f imparts higher dynamic impact on the soil leading to a reduction in M_R. However, M_R reduction under $f = 2$ Hz and 4 Hz is negligible indicating that a further increment in f did not contribute to M_R reduction which is due to the quick application and release of loading cycle at $f = 4$ Hz. Such behaviour was not observed when loading frequency was applied in stages from $f = 1$ to 4 Hz where an increase in M_R can be observed. This is mainly because a packet of 1000 loading cycles at $f = 2$ Hz densified the soil and increased the soil resiliency, however, the increment was non-linear. Figure 7b shows the plot of M_R with Bishop′s stress p^* ($p_{net} + Srs$, where $p_{net} = (\sigma_1+2\sigma_3)/3$ is mean net stress and S_rs is suction stress. The results indicate that the increment in p^*increases the inter-granular bonding which increased M_R.

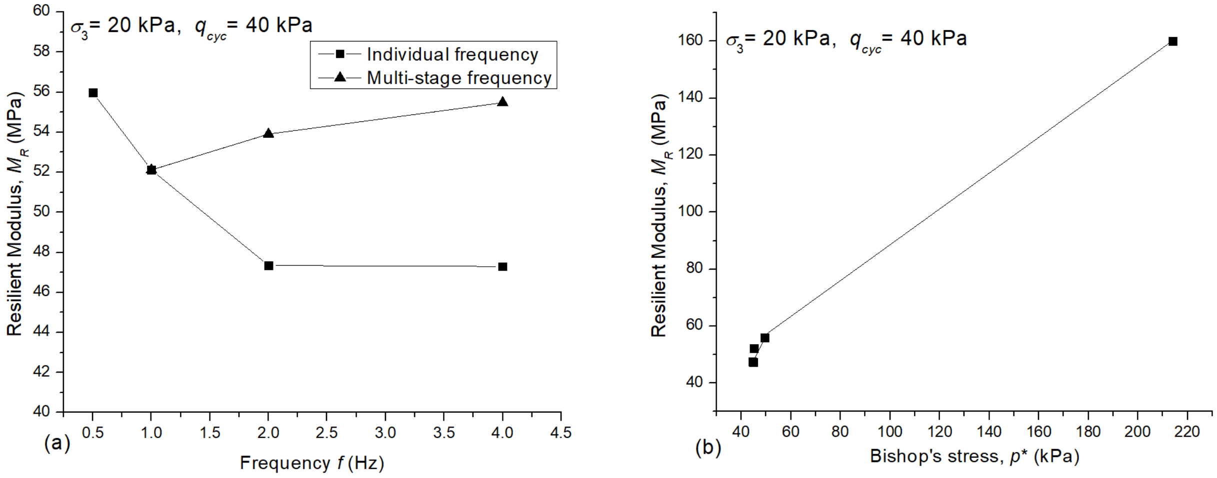

Figure 7. Resilient Modulus: (a) effect of frequency (b) in terms of Bishop′s stress

CONCLUSIONS

This paper presents the impact of cyclic loading frequency applied individually and in stages on an unsaturated compacted clayey sand. Stress-controlled cyclic triaxial testing was carried out while the evolution of suction and degree of saturation were monitored continuously. It was observed that the strain accumulation during individually applied cyclic frequency was dependent on the magnitude of cyclic frequency indicating the indirect application of higher dynamic impact on frequency increment. However, such dependency was not observed during the multi-stage frequency loading. This behaviour was consistent with the evolution of suction (maximum suction change) and degree of saturation during the first packet of the loading cycles. The suction reduction and then equalisation was dependent on the water retention state of the sample where a dry of optimum sample took a longer duration for equalisation compared to a wet of optimum sample. The resilient modulus was dependent on the frequency application procedure where reduction in the resilient modulus was observed when f was individually increased whereas such dependency was not observed for the case of multi-stage loading frequency mainly because of stabilization of soil particles during the first packets of loading cycles. Also, the increment in Bishop′s stress increased the inter-granular bonding leading to an increment in resilient modulus.

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