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Rate-dependency and Stress-Relaxation of Unsaturated Clays

Meghdad Bagheri[1] Ph.D.; Mohammad Rezania[2] Ph.D.; Mohaddeseh Mousavi Nezhad[3] Ph.D.

Abstract

This paper presents the experimental program conducted for evaluation of the rate-dependent and stress-relaxation behaviour of unsaturated reconstituted London Clay. A series of drained constant rate of strain (CRS) compression-relaxation tests with single-staged (SS-CRS) and multi-staged (MS-CRS) loading modes were performed in an innovative CRS oedometer cell where soil suction evolutions were monitored using two high-capacity tensiometers (HCTs). Specimens were tested at two strain rates of 4.8×10^{-7} and 2.4×10^{-6} s^{-1} and over a suction range of 0 – 1905 kPa. The coupled and independent effects of strain-rate and soil suction on one-dimensional stress–strain and stress-relaxation responses including the effects of pre-relaxation strain, stress, and strain-rate under both saturated and unsaturated conditions were evaluated. An increase in suction and strain-rate resulted in an increase of the yield vertical net stress (σ_p). Furthermore, it was observed that the rate and magnitude of the relaxed stresses increase with increase in pre-relaxation strain, stress, and strain-rate, and decrease with increase in soil suction. At constant suction, an increase in the pre-relaxation strain-rate by a factor of 5 resulted

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[1] Lecturer, School of Energy, Construction and Environment, Coventry University, Coventry, UK.
Email: ac6031@coventry.ac.uk. ORCID: https://orcid.org/0000-0002-9748-4165

[2] Associate Professor, School of Engineering, University of Warwick, Coventry, UK. (Corresponding Author)
Email: m.rezania@warwick.ac.uk. ORCID: https://orcid.org/0000-0003-3851-2442

[3] Associate Professor, School of Engineering, University of Warwick, Coventry, UK.
Email: m.mousavi-nezhad@warwick.ac.uk. ORCID: https://orcid.org/0000-0002-0625-439X

in an increase of the relaxed stresses by a factor of 2.2 – 3.6. Moreover, the coefficient of relaxation (R_α) was found to be suction-dependent, falling within a range of 0.011 – 0.019 and 0.017 – 0.029 respectively for slow and fast strain rates during MS-CRS tests. Comparing these results with the C_α/C_c ratio obtained from conventional multi-stage loading (MSL) oedometer test results revealed the validity of $R_\alpha = C_\alpha/C_c$ correlation for unsaturated reconstituted specimens.

Author Keywords: Stress-relaxation, Strain-rate, Suction, Unsaturated soils

Introduction

The hydro-mechanical behaviour of natural clays is highly influenced by time and rate effects (Bagheri et al. 2015). The time- and rate-dependent soil parameters are the key factors for design, analysis, and construction of geotechnical structures. The effect of strain-rate is highlighted in staged construction of geo-structures where each stage of the construction plan alters the rate of soil straining in the ground. Furthermore, the construction plans often involve stages of constant total strain in the soil body during which the effective stress decreases continuously with time at a very slow rate, a phenomenon known as stress-relaxation. For instance, the soil behind supported walls of an excavation may exhibit stress-relaxation as the soil straining is restricted. Moreover, clay deposits subjected to prolonged sustained loading exhibit significant deformations with time, a phenomenon known as creep. In recent years significant attention has been given to characterisation of rate-dependency, creep, and stress-relaxation of saturated clays (e.g. Kim and Leroueil 2001; Yin and Hicher 2008; Karstunen et al., 2010; Sorensen et al., 2010; Tong and Yin, 2013; Yin et al., 2014; Rezania et al., 2017a; Rezania et al. 2017b). However, very few studies can be found in the literature accounting for the time- and rate-dependent response of unsaturated clays, this being, in part, due to the difficulties associated with the control of several parameters (i.e. time, stress, strain, suction, etc.) in an experiment. Lai et al. (2010) studied the effect of suction on creep strain-rate and magnitude of reconstituted clays from the sliding zone soils of the Qianjiangping landslide in triaxial conditions and reported a decrease in creep strains with an increase in soil suction. Nazer and Tarantino (2016) investigated the viscous response (in both creep and relaxation modes) during shearing of reconstituted Ball clay using shear box and developed an analogue model for simultaneous modelling of creep and relaxation. Wang et al. (2017) performed a set of triaxial stress-relaxation tests on unsaturated lime-treated expansive clays of Hefei Xianqiao Airport site in China, at suctions of 50 and 100 kPa, and studied the effects of pre-relaxation strain level, pre-relaxation strain-rate, and relaxation time. The authors reported that for stress levels below peak deviator stress, larger relaxed stresses were observed with increase in pre-relaxation strain. Conversely, for stresses higher than the peak strength, smaller relaxed stresses were observed for higher pre-relaxation strain levels. A clear explanation of suction effects on the stress-relaxation process was not, however, presented. According to Ladanyi and Benyamina (1995), investigation of the stress–strain–time behaviour of soils can be done more conveniently by performing stress-relaxation tests rather than conventional creep tests. However, due to the lack of a unified and widely accepted formulation for correlating stress-relaxation and strain-rate-dependency and creep parameters, stress-relaxation tests have not been widely used for determination of the time-dependent response of soft soils (Borja 1992; Yin et al. 2014).

This paper presents the results of constant rate of strain (CRS) compression-relaxation tests on reconstituted London Clay under saturated and unsaturated conditions. An advanced suction- and temperature-controlled CRS oedometer apparatus equipped with two high-capacity tensiometers (HCTs) for monitoring suction evolutions is used for conducting the experiments. The coupled effects of strain-rate and suction on compression characteristics is investigated. Furthermore, the effect of suction, pre-relaxation strain-rate, strain, and stress level on the stress-relaxation response is evaluated from a set of single-staged and multi-staged compression-relaxation tests.

Test Material and Apparatus

The material used in this study is London Clay (LC) which was collected from an engineering site in the Isle of Sheppey, UK. The natural samples were oven dried then crushed into powder and sieved through 1.18 mm opening sieve. The powder containing some course-grained peds (or large size clay clusters) was then mixed with distilled de-aired water at $1.5w_L$. Reconstituted samples were prepared by consolidating the soil slurry in a large diameter Perspex consolidometer. The obtained soil cake was then dried at ambient temperature to pre-specified water contents following the procedure discussed in Bagheri et al. (2019). Finally, the oedometer specimens were cored from the unsaturated samples using the cutting ring. Table 1 presents the index and physical properties of the tested material. It must be noted that the presence of course-grained peds resulted in an air-entry value (AEV) of around 250 kPa (Bagheri et al. 2019) which is notably lower than the AEV of natural LC reported in the literature. The lower AEV allows for testing specimens over a wider range of soil suctions in unsaturated states. All experiments were carried out on reconstituted specimens in order to eliminate the effect of soil structure (mainly inter-particle bonding) on the test results.

An advanced suction- and temperature-controlled CRS oedometer cell (see Bagheri et al. 2019) was used for conducting CRS compression and relaxation tests under saturated and unsaturated conditions. The new CRS oedometer system made it possible to perform multi-staged tests which included 1D compression tests; (1) at a constant rate of strain to investigate the coupled effects of suction and strain-rate, and (2) with rest periods at intermediate stages with fixed axial strain to investigate the effects of suction, pre-relaxation strain, stress, and strain-rate on the stress-relaxation behaviour. Fig. 1 presents a schematic diagram of the apparatus. Two

HCTs, accommodated at the mid-height of the specimen, allowed for continuous measurement of pore-water pressure (suction) evolutions throughout the experiments (see Bagheri et al. 2018 for more information about the design characteristics of the HCTs).

Experimental Program

Drained CRS compression tests were carried out on saturated and unsaturated specimens at two different strain-rates of $\dot{\varepsilon_v} = 4.8\times10^{-7}$ (denoted by letter A) and $\dot{\varepsilon_v} = 2.4\times10^{-6}\ s^{-1}$ (denoted by letter B). Two types of tests were carried out; single-staged compression-relaxation tests (SS-CRS), and multi-staged compression-relaxation tests (MS-CRS). A set of 10 drained SS-CRS tests were carried out, each test comprising of two stages; (1) loading the specimen at a constant rate of displacement to a vertical total stress of $\sigma_0 \cong 3450$ kPa, and (2) stress-relaxation at zero rate of axial displacement for a period of at least $t_R \cong 210$ hours. This set of experiments allow for investigation of suction and strain-rate effects on the compression and stress-relaxation processes. Table 2 summarises the details of the compression stage of the SS-CRS tests.

A set of two MS-CRS tests were carried out on unsaturated specimens, having an initial suction of $s_0 \cong 701$ kPa (initial water content of $w_0 = 33\%$). The test procedure involved loading the specimens at a constant rate of displacement with stress-relaxation stages of 24 hours duration set at different strain levels as summarised in Table 3. This set of experiments allow for investigation of pre-relaxation strain level, stress level, and strain-rate on the stress-relaxation process. Before commencing each experiment, the preparation of the cell was carried out according to the procedure described in Bagheri et al. (2019). The HCTs were also preconditioned (see Bagheri et al. (2018) for more details). All tests were performed in a temperature-controlled laboratory environment to avoid the influence of temperature fluctuations on the output data. The maximum values of PPR (denoted by PPR_{max}) for selected strain-rates were found to be within a range of 1 – 9%, complying well with the suggested PPR_{max} range of 3 – 15% by ASTM-D4186-06 (2006). PPR is defined as the ratio of the excess pore-water pressure (u_{exc}) to the applied vertical total stress (σ_v).

The experimental results of saturated tests are evaluated based on the effective stress principle ($\sigma'_v = \sigma_v - u_w$). Simplified methods for calculation of unsaturated effective stress based on the single effective stress approach can be found in Khoshghalb and Khalili (2013) and Khoshghalb et al. (2015). However, in this work, the experimental results of unsaturated tests are evaluated based on the vertical net stress ($\sigma_{vnet} = \sigma_v - u_a$). Since the tests were carried out at the atmospheric air pressure, the vertical net stress is equal to the applied vertical total stress. Where the results of saturated and unsaturated CRS tests were to be plotted on the same graph, the saturated tests were also interpreted based on vertical net stress. Moreover, in order to allow for comparing the results with those reported in the literature, the mechanical path is represented in terms of axial strain (ε_a) and σ_{vnet}. The compression index (C_c) is calculated as the slope of the normal compression line (NCL) of the compression curve plotted in $e/e_0 - \log \sigma_{vnet}$ space, where e/e_0 represents the void ratio (e) normalised with respect to the initial void ratio (e_0). The yield vertical net stress (σ_p) is determined as the intersection of the best fitted lines to the pseudo-elastic and plastic sections of the compression curve. The stress-relaxation process is evaluated using three main parameters; the coefficient of relaxation (R_α), the residual stress ratio (ξ), and the relaxed stress ($\Delta\sigma$). R_α is defined as the slope of the plot of σ_{vnet} versus time (t) in $\log \sigma_{vnet} - \log t$ space during relaxation of the stresses;

$$R_\alpha = -\frac{\Delta \log(\sigma_{vnet})}{\Delta \log(t)} \tag{1}$$

The residual stress ratio (ξ) is defined as the ratio of the residual total vertical stress (σ_s) and the pre-relaxation total vertical stress (σ_0). The residual total vertical stress is the stress value at the end of the relaxation course.

$$\xi = \frac{\sigma_s}{\sigma_0} \tag{2}$$

The relaxed stress ($\Delta\sigma$) is defined as;

$$\Delta\sigma = \sigma_0 - \sigma_s \tag{3}$$

Similar parameters were introduced by Wang et al. (2017) for interpretation of the stress-relaxation process in triaxial conditions.

Discussion of the Results

Effect of Suction and Strain-rate on Stress-Relaxation Response

Fig. 2 illustrates the results of the compression stage of the SS-CRS tests. Also shown in the graphs, are the change in pore-water pressure ($\Delta u = u_w - u_{exc}$) with σ_{vnet}. As the pore-water pressure (suction) measurements recorded by the two HCTs installed on each specimen were very similar, only measurements from one of the HCTs are presented in the graphs.

Inspection of the results reveals the suction-dependency of the stress–strain behaviour during 1D compression. As can be seen, the overall compressibility of the specimens decreases with increase in suction and strain-rate. Moreover, increase in suction resulted in an increase in σ_p values for both sets of experiments carried out at different strain-rates. The values of σ_p vary with strain-rates at the strain level of 2 – 3%. Slope of the normal consolidation lines (NCLs) for both sets of tests were found to be suction-dependent and decrease with increase in suction, within the range of applied vertical stresses. This effect was more pronounced for higher strain-rate tests. Furthermore, by extrapolating the compression curves to higher stress levels (i.e. greater than 3.5 MPa), it is anticipated that the slope of NCLs will eventually converge at a constant value corresponding to that of saturated specimen, as suggested by Zhou et al. (2012). Inspecting the variation of u_{exc} with σ_{vnet} reveals that the higher the strain-rate, the higher the generated u_{exc}. The rate of change of Δu was also found to decrease with increase in suction.

Fig. 3 presents a comparison of the compression curves obtained from CRS test and the conventional multi-staged loading (MSL) oedometer tests (Bagheri 2018) for saturated specimens (prepared with similar procedure) with w_0 of 43 and 39%. It is observed that the compression curves from CRS tests are shifted to the right, exhibiting higher preconsolidation pressure than the MSL tests. Moreover, the figure shows that at a given void ratio, the higher the strain-rate the higher the vertical effective stress. The strain-rate values chosen for the CRS tests are generally higher than the observed strain-rates during creep phases of conventional oedometer tests. This results in the CRS compression curves lying above the MSL compression curves. Selection of very slow strain-rates, in addition to significantly increasing testing time, can give rise to aging effects and gradual development of inter-particle bonding, which leads to an increase in σ_p and shift of the CRS compression curve to the right (Leroueil et al. 1996; Qiao et al. 2016). This is also the case when a specimen, subjected to prolonged creep at very low strain-rates, is loaded (Sorensen et al. 2010). A CRS compression curve with a very slow strain-rate may also lie above a CRS compression curve with much faster strain-rate, due to the aging effects.

Fig. 4 presents the variation of σ_p with suction for both MSL and CRS tests. It is observed that at a constant suction, the higher the strain-rate, the higher the σ_p. Similarly, at a constant strain-rate, the higher the suction, the higher the σ_p. Additionally, the increase in σ_p with suction appears to follow an approximately linear trend for fast, slow, and oedometric strain-rates. An average value of 1.3 has been reported in the literature for the ratio of σ_p obtained from CRS and MSL tests ($\sigma_{pCRS}/\sigma_{pMSL}$) on saturated soft clays for strain-rates in a range of 1×10^{-6} to 4×10^{-6} s^{-1} (Leroueil et al. 1983; Hanzawa et al. 1990; Nash et al. 1992; Cheng and Yin 2005). The $\sigma_{pCRS}/\sigma_{pMSL}$ ratio for specimens with $w_0 = 0.39$ (saturated) is calculated as 1.29 which is very close to the average value reported for soft clays in abovementioned studies. This ratio can therefore be considered as a function of the loading mode rather than the sample type (i.e., intact or reconstituted).

As mentioned earlier, the stress-relaxation process was initiated right after the test specimens, loaded at different strain-rates of A and B, reached a maximum vertical stress of approximately 3450 kPa. The gradual decrease of stresses with time were recorded and used for evaluation of the effects of pre-relaxation strain-rate, relaxation time (t_R), and suction, on the stress-relaxation process. Monitoring suction evolutions during the course of stress-relaxation for CRSru26-A and CRSru26-B, having initial suctions of approximately 1905 kPa, was interrupted due to the cavitation of the HCTs. Due to the sensitivity of the stress-relaxation stage, no attempt was made to replace the cavitated HCTs, and hence, the suction measurements are not available for these two experiments. The final values of soil suction were, however, measured at the end of the tests. Table 4 summarises the characterisation parameters. In order to provide a platform for comparison, the values of σ_s corresponding to $t_R = 210$ hours are used for calculation of the relaxation parameters $\Delta\sigma$, ξ, and R_α.

Considering the values of relaxation parameters given in Table 4, it is found that, at constant pre-relaxation stress (σ_0), increase in suction resulted in a decrease of the relaxed stresses ($\Delta\sigma$) and consequently an increase of the stress-relaxation ratio (ξ). In other words, with increase in suction from 0 to 1905 kPa, the ratio $\Delta\sigma/\sigma_0$ was reduced from 21 to 14% for specimens loaded at the slow strain-rate (A), and from 23 to 18% for specimens loaded at the fast strain-rate (B).

Effect of suction in reduction of relaxed stresses appears to be reasonable, considering the stress-relaxation mechanism as a time-dependent process of particles re-adjustment and gradual change in the structural configuration of grains. In essence, the additional bonding forces exerted by the under-tension water menisci developed at the inter-particle contacts, can prevent re-arrangement of particles, and hence, release of stresses accumulated during the loading stage.

Fig. 5 presents the relaxation of vertical stress with time in a semi-log plot. Also shown in the graphs, are the plots of dissipation of u_{exc} with time during the stress-relaxation stage. The process of stress-relaxation appears to involve three phases of; (1) fast relaxation, (2) decelerating relaxation, and (3) residual relaxation as schematically shown in Fig. 6. The fast relaxation phase is associated with a quick release of the main accumulated energy inside the specimen, whereas the deceleration and residual phases correspond to the time-dependent particles re-arrangement which involves further dissipation of energy with time. At a constant strain-rate, suction appears to have more influence on the stress-relaxation process during fast and deceleration phases. In fact, the higher the suction, the lower would be the rate of relaxation during fast and decelerating relaxation phases. Similarly, at a constant suction, the higher the pre-relaxation strain-rate, the higher would be the rate and magnitude of the relaxed stresses as shown in Fig. 7 for CRSru26-A and CRSru26-B specimens (see also Table 4 for corresponding relaxation parameters). Similar observations were reported by Wang et al. (2017) from the results of triaxial stress-relaxation tests on unsaturated lime-treated expansive clay specimens.

It must be noted that, except for the saturated specimens where a slight drainage of water was observed, the processes of u_{exc} dissipation did not involve any significant volume change, given the preservation of suction state in the unsaturated specimens. Effect of pore-water pressure dissipation during relaxation stage of 1D CRS tests on saturated reconstituted LC was also reported by Sorensen (2006).

Fig. 8 presents the variation of relaxation coefficient (R_α) with suction for fast and slow strain-rates. Although there is a clear difference between the R_α values corresponding to saturated ($s = 0$) and unsaturated (e.g. $s = 1905$ kPa) states, with the limited number of data points, it is hard to comment on the relationship between R_α and suction. For the slow and fast strain-rates, the values of R_α fall within a range of 0.011 – 0.019 and 0.017 – 0.029 respectively. As suggested by Yin et al. (2014), the values of R_α are equal to the values of $\alpha = C_\alpha/C_c$ ratio and can be used for estimation of creep index (C_α) and compression index (C_c). Bagheri (2018) showed that the values of α were also suction- and stress-dependent and fall within a range of 0.023 – 0.030 for MSL tests on unsaturated reconstituted LC specimens. This range, with a good approximation, complies with the R_α range of 0.017 – 0.029 obtained from fast strain-rate tests, hence, validating the applicability of $R_\alpha = \alpha$ for saturated and unsaturated reconstituted specimens tested in this study.

Effect of Pre-relaxation Stress Level

Fig. 9 illustrates the variations of σ_v with time during MS-CRS tests. Also shown in the graphs, are the change in pore-water pressure (Δu) with time (dotted lines). The characterisation parameters for stress-relaxation stages are summarised in Table 5. In order to provide a platform for comparison, the values of σ_s corresponding to $t_R = 24$ hours are used for calculation of the relaxation parameters $\Delta\sigma$, ξ, and R_α.

The values of relaxed stresses ($\Delta\sigma$) are found to increase with increase in the pre-relaxation strain (ε_R) for the specimen loaded at the slow strain-rate. However, the values of $\Delta\sigma/\sigma_0$ ratio increase from 21 to 24% for an increase in ε_R from 5 to 10%, then decrease to 22 and 20% respectively for pre-relaxation strains of 15 and 18%. Similarly, for the specimen loaded at the fast strain-rate, the values of $\Delta\sigma$ are found to increase with increase in the pre-relaxation strain up to 15% at which it decreases to a lower value at $\varepsilon_R = 17\%$. The values of $\Delta\sigma/\sigma_0$ ratio increase from 43 to 58% for an increase in ε_R from 5 to 10%, then decrease to 55 and 44% respectively for pre-relaxation strains of 15 and 17%. Overall, larger relaxed stresses are observed with increase in pre-relaxation strains (and consequently pre-relaxation stresses). Moreover, an increase in the pre-relaxation strain-rate by a factor of 5, is found to significantly affect the magnitude of relaxed stresses at each pre-relaxation strain level, resulting in an increase of the $\Delta\sigma$ values by a factor of 2.2 – 3.6.

Fig. 10 presents the variations of relaxed stresses with time in a log-log scale. Higher stress-relaxation rates are observed for higher pre-relaxation strains. Furtheremore, an approximately linear relationship between the vertical total stress and time is observed during relaxation stage and after dissipation of u_{exc}. Similar results have been reported in the literature for saturated soft clays (e.g. Yin and Graham 1989; Kim and Leroueil 2001; Yin et al. 2014).

As shown in Table 5, with change in ε_R, values of R_α vary within the ranges of 0.011 – 0.027 and 0.025 – 0.035 respectively for slow and fast pre-relaxation strain-rates (Fig. 11), indicating dependency of the relaxation coefficient to the pre-relaxation strain (or stress) and strain-rate. The observed ranges of R_α for the 24 hours relaxation stages of MS-CRS tests are, however, higher than the ranges obtained from SS-CRS tests with minimum of 210 hours relaxation duration. In essence, the higher calculated R_α values for MS-CRS tests appear to correspond to the decelerating relaxation phase, characterised with higher relaxation rate, whereas the R_α values for SS-CRS tests correspond to the residual relaxation phase, characterised with lower relaxation rate. Larger relaxation periods are, therefore, required for better estimation of relaxation coefficient, and hence, more accurate determination of time-dependent parameters based on $R_\alpha = C_\alpha/C_c$ relationship.

Conclusion

Results of a set of SS-CRS and MS-CRS oedometer tests performed on reconstituted London Clay specimens under saturated and unsaturated conditions and varied strain-rates were presented. From the test data, the following conclusions can be drawn;

1) Increase in strain-rate results in an increase in σ_p and decrease in C_c values. Similar effects were also observed with increase in suction.
2) Compression curves from CRS tests exhibit higher σ_p than the MSL tests. Moreover, at a given void ratio, the higher the strain-rate the higher would be the vertical stress.
3) At a constant suction, the higher the strain-rate, the higher the σ_p. Similarly, at a constant strain-rate, the higher the suction, the higher the σ_p.
4) Increase in σ_p with suction appears to follow an approximately linear trend for fast, slow, and oedometric strain-rates.
5) The process of stress-relaxation consists of three phases; (1) fast relaxation, (2) decelerating relaxation, and (3) residual relaxation.
6) At a constant pre-relaxation stress (σ_0), increase in suction results in a decrease in the rate of stress-relaxation during fast and decelerating relaxation phases, as well as in the magnitude of the overall relaxed stresses ($\Delta\sigma$).
7) At a constant suction, the higher the pre-relaxation strain-rate, the higher would be the rate and magnitude of the relaxed stresses.
8) The $R_\alpha = C_\alpha/C_c$, suggested by Yin et al. (2014) for saturated soft clays, was observed, with an approximation, to also be valid for unsaturated reconstituted specimens in the range of applied vertical stresses and soil suctions in this study.
9) A higher rate and magnitude of relaxed stresses were observed with increase in pre-relaxation strains (and consequently pre-relaxation stresses).

10) At a constant strain level and suction, an increase in the $\Delta\sigma$ values by a factor of 2.2 – 3.6 was observed with an increase in the pre-relaxation strain-rate by a factor of 5. At the same strain level, increase in pre-relaxation strain-rate also results in an increase in R_α values under constant suction.

11) More test results over a wider range of suctions and strain-rates are required for adequately characterisation of the pre-relaxation strain-rate effect on the stress-relaxation process in unsaturated clays.

Notations

The following symbols are used in this paper:

e = void ratio
e_0 = initial void ratio
s = soil suction
s_0 = initial suction
t = time
t_R = relaxation duration
u_a = pore-air pressure
u_{exc} = excess pore-water pressure
u_w = pore-water pressure
w = gravimetric water content
w_0 = initial gravimetric water content
w_L = liquid limit
w_P = plastic limit
C_c = compression index
C_r = reloading index
C_s = swelling index
C_α = creep index
D = particle diameter
G_s = specific gravity
I_p = plasticity index
R_α = coefficient of stress-relaxation
α = represents the ratio C_α/C_c
ε_a = axial strain

ε_R = pre-relaxation strain
$\dot{\varepsilon}_v$ = strain-rate
σ_0 = pre-relaxation total vertical stress
σ_p = yield vertical net stress
σ_v = applied vertical total stress
σ_s = residual total vertical stress
σ'_v = vertical effective stress
σ_{vm} = maximum applied vertical stress
σ_{vnet} = vertical net stress
σ_{pCRS} = yield vertical net stress obtained from CRS tests
σ_{pMSL} = yield vertical net stress obtained from MSL tests
$\Delta\sigma$ = relaxed stress
Δu = change in pore-water pressure
ζ = residual stress ratio
AEV = air-entry value
HCT = high-capacity tensiometer
LC = London clay
MSL = multi-staged loading
NCL = normal compression line
SSL = single-staged loading
CRS = constant rate of strain
1D = one-dimensional
PPR = pore-water ratio

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