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An Experimental study of the initial volumetric strain rate effect on the creep behaviour of reconstituted clays

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Abstract. Clayey soils tend to undergo continuous compression with time, even after excess pore pressures have substantially dissipated. The effect of time on deformation and mechanical response of these soft soils has been the subject of numerous studies. Based on these studies, the observed time-dependent behaviour of clays is mainly related to the evolution of soil volume and strength characteristics with time, which are classified as creep and/or relaxation properties of the soil. Apart from many empirical relationships that have been proposed in the literature to capture the rheological behaviour of clays, a number of viscid constitutive relationships have also been developed which have more attractive theoretical attributes. A particular feature of these viscid models is that their creep parameters often have clear physical meaning (e.g. coefficient of secondary compression, C_α). Sometimes with these models, a parameter referred to as initial/reference volumetric strain rate, $\dot{v}_0$ has also been alluded as a model parameter. However, unlike C_α, the determination of $\dot{v}_0$ and its variations with stress level is not properly documented in the literature. In an attempt to better understand $\dot{v}_0$, this paper presents an experimental investigation of the reference volumetric strain rate in reconstituted clay specimens. A long-term triaxial creep test, at different shear stress levels and different strain rates, was performed on clay specimen whereby the volumetric strain rate was measured. The obtained results indicated the stress-level dependency and non-linear variation of $\dot{v}_0$ with time.

1. Introduction

In recent decades, the population growth in urban areas and the subsequent increase in the demand for accommodation and new infrastructure (e.g. buildings, roads, railways, and tunnels) have resulted in the infrastructure construction on soils of marginal quality such as soft to very soft soils which are known to behave in such a way that are highly influenced by the time effects. Soft soils such as clays undergo continuous compression with time even after excess pore water pressure is dissipated. These deformations (creep), which mainly occur over a long duration of time, cause difficulties for the serviceability limit state design of infrastructures and if this is not controlled, it may lead to potential geohazards and infrastructure instabilities. A significant number of studies have been conducted over the past few decades to develop empirical correlations and constitutive models capable of capturing the rheological behavior of clays. This has led to the introduction of various empirical correlations (e.g. [1]) and the emergence of diverse conceptual theoretical frameworks such as the concept of isotaches [2], the overstress theory [3], and the concept of non-stationary flow surface [4], from which advanced constitutive time- and rate-dependent soil models were developed. Among these, there are

viscid constitutive relationships (e.g. [5]) which their creep parameters, mainly coefficient of secondary compression, C_α, and initial/reference volumetric strain rate, $\dot{v}_0$ possess clear physical meanings. A thorough understanding of the variations of these key parameters with time and stress level can further support the applicability of viscid models for accurate prediction of the rheological behavior of natural clays in field conditions. C_α, has received significant attention in the past 50 years and a substantial amount of information is available in the literature to describe its variation with various influencing factors such as time, consolidation pressure, soil structure, and sustained loading [6, 7, 8]. Unlike C_α, volumetric strain rate, $\dot{v}$, and its reference value, $\dot{v}_0$, have been the subject of a very few studies in the past. In one of the first studies of the creep behavior of normally consolidated clays under drained and undrained triaxial conditions, Singh and Mitchell [9] reported that the volumetric creep strain rate increases with the applied deviatoric stress. Tavenas et al. [10] studied the effect of stress state (p', q) during the triaxial creep tests on lightly overconsolidated undisturbed Saint-Alban clay. It was observed that there was a slight increase of volumetric strain rate with effective mean stress (p'), as well as an increase in axial strain rate (ε_d) with increase in deviatoric stress (q). These reports along with some other related information in the literature approve the stress-dependency of $\dot{v}$. Furthermore, there is general agreement that during the secondary compression, the volumetric strain rate, $\dot{v}$, varies linearly with the rate of change of time logarithm. However, a few studies can be found in the literature which can suitably demonstrate stress dependency and evolution with time of $\dot{v}_0$ during the secondary compression. In this paper we endeavor to experimentally investigate this parameter under triaxial conditions.

2. Triaxial creep test

2.1. Apparatus
A fully automated triaxial testing system was utilized to study the evolution of volumetric strain rate during the creep test. The triaxial system is based on the classic Bishop-Wesley type stress path cell which enables control of stresses directly on the sample. The fundamental system hardware elements are shown in Figure 1. The system is composed of a cell pressure/volume controller, a back pressure/volume controller, a lower chamber pressure/volume controller as a hydraulic axial loading driver, high accurate transducers and a data acquisition system. The apparatus can meet the needs of the creep test under constant stress and the stress relaxation test under constant strain, respectively. Accurate monitoring of specimen volume change, stresses and strains are obtained from the feedback of the automatic controllers and transducers.
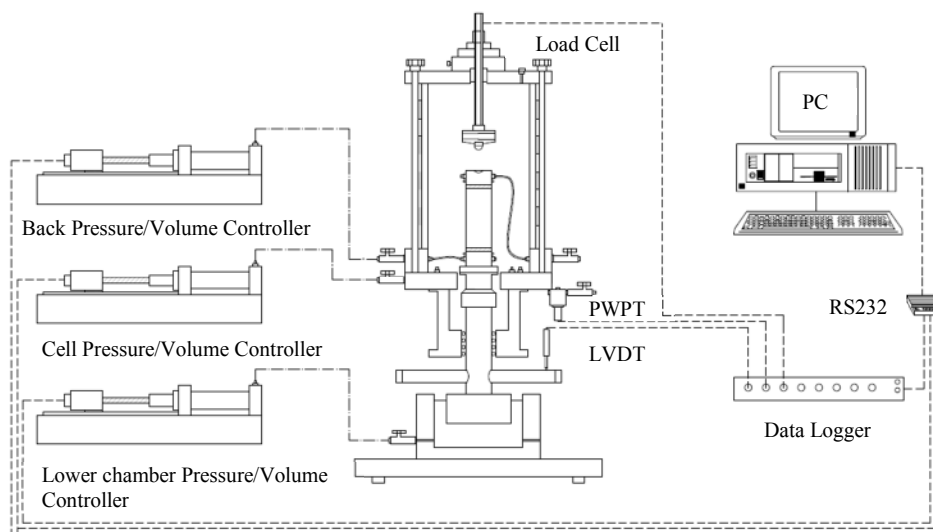

Figure 1. Automatic stress-path triaxial testing system

2.2. Testing material and sample preparation

The material investigated in this study was London Clay extracted from an excavation site in The Isle of Sheppey, UK. The Properties of the tested material are given in Table 1. A triaxial specimen of 50mm in diameter and 99mm in height was prepared by the moist tamping method (dynamic compaction). The soil specimen was compacted at the initial water content of 20 % to a specific volume of 1.95. The soil specimen was compacted dynamically in 9 layers on the base pedestal of the triaxial cell. In order to achieve better uniformity, the compaction method proposed by Ladd [11] was adopted. In this method, the uniformity of the soil specimen can be achieved by compacting the top, middle, and bottom thirds proportions of the specimen at 4% denser than the desired dry density, equal to the desired dry density, and 4% looser than the desired dry density, respectively.

Table1. Index properties of the testing material (London Clay)

Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Specific Gravity	In-situ Water Content (%)
78	24	54	2.67	30-34

2.3. Testing program and procedures

To study the stress-level dependency and the time evolution of the volumetric strain rate, a multistage triaxial drained creep test was carried out on the re-compacted specimen. The test procedure involved the following three stages; (1) Saturation: the specimen was saturated gently by using low rates of saturation ramp, i.e. ramping cell pressure and back pressure at the same time and at the same rate so the apparent state of effective stress (here 20 kPa) was maintained. The Saturation stage was completed after approximately 10 days under maximum cell and back pressures of 700 kPa and 680 kPa respectively. (2) Consolidation: the specimen was consolidated isotropically under two levels of mean total stress p_1=100 kPa, and p_2=200 kPa. (3) The Incremental drained creep test: with the value of p being constant the specimen was loaded at a constant rate of strain to certain stress states (p, q). Appropriate loading rates were considered for the loading stages so the development of excess pore pressure was kept at a very low range. Each effective stress increment was sustained for a fixed period of 120 hours and the resultant creep deformations and volume changes were monitored for every hour. De-stilled de-aired water was used for this experiment in order to minimize the effects of algae growth and air dissolution on the volume change measurements during the long-term test.

3. Results

The overall test duration including saturation, consolidation, incremental loading, and 4 creep stages took about 35 days. Therefore, the obtained results were corrected for the effects of water absorption into the cell body as well as the creep expansion of the cell's body. Figure 2 presents the incremental loading and creep stages of the test on the graph of deviator stress, q, versus axial strain, ε_d.

Figures 3 and 4 present the volumetric strain – time and the volumetric strain rate – time responses at different applied deviatoric stresses, respectively. The Stress-level dependency and time-dependency of both v and $\dot{v}$ are clearly observed on these graphs. The magnitude and rate of volumetric strain tends to increase with the deviatoric stress. In terms of time-dependent response, unlike the volumetric strain which shows a linear increasing trend with time, the volumetric strain rate is decreased non-linearly with elapsed time. These findings are in good agreement with other works performed on various clayey soils and cited in the literature. The slight deviation of the plots of v and $\dot{v}$ for q=10.2 kPa in Figures 3 and 4 can be interpreted as a possible fundamental modification in the soil structure and the development of reverse resistance as a result of aggregates structuration.
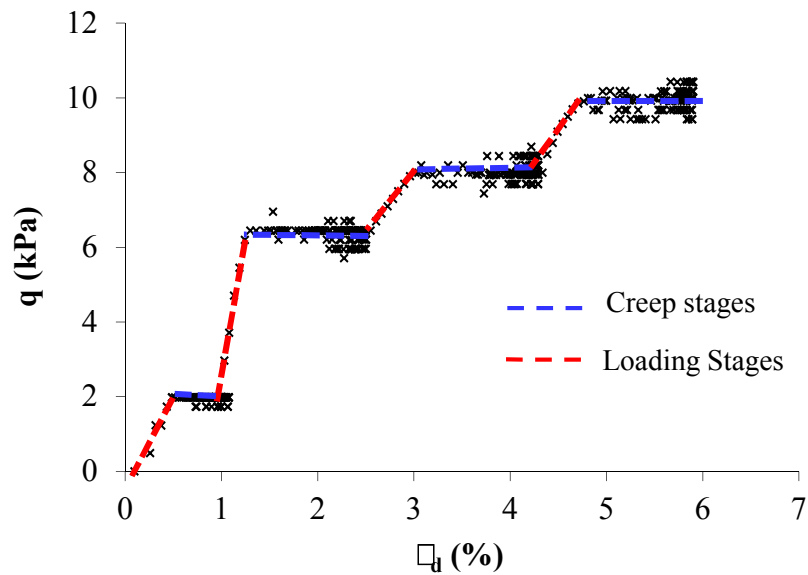
Figure 2. Stress – strain relationship during incremental loading and creep stages.

Figures 5 and 6 show the variation of $\dot{v}_0$ with time and stress-level respectively. Here, the $\dot{v}_0$ is referred to as the volumetric strain rate immediately before the change in loading. Note that the $\dot{v}_0$ values are based on the average volumetric strain rates in the last two hours of each creep stage. Interestingly, it can be observed in Figure 5 that the $\dot{v}_0$ values tend to increase with time but with a decreasing rate. In addition to the time-dependency, the stress-dependency of $\dot{v}_0$ is also approved as shown in Figure 6. It is worth to mention here that, although the $\dot{v}_0$ values tend to increase with the increase in deviatoric stress at the initial stages of creep at constant stress, but without obtaining more data points from the final test stages, it is hard to comment on the overall effect of the deviatoric stress on the $\dot{v}_0$, and whether the trend exhibits a decreasing or an increasing rate. However, these observations are sufficient to contradict the general assumption of $\dot{v}_0$ as a material constant of the viscid theory proposed initially by Sekiguchi [12] and modified by Sekiguchi and Ohta [5].
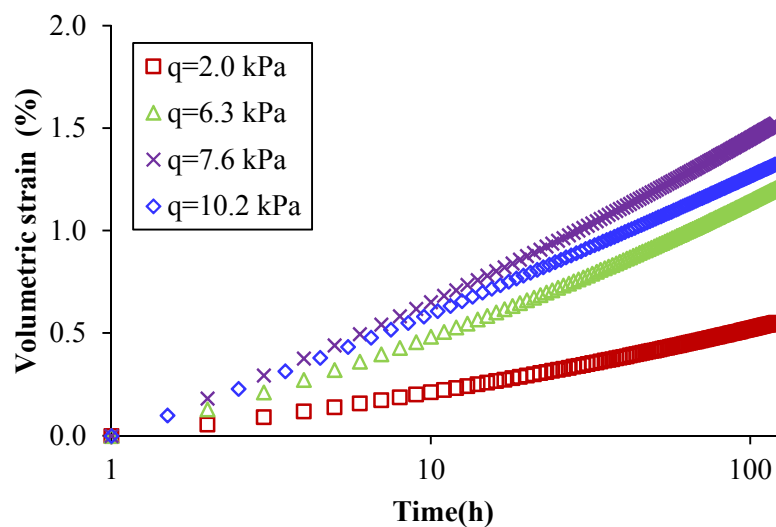

Figure 3. Volumetric strain – time response at different deviator stresses.
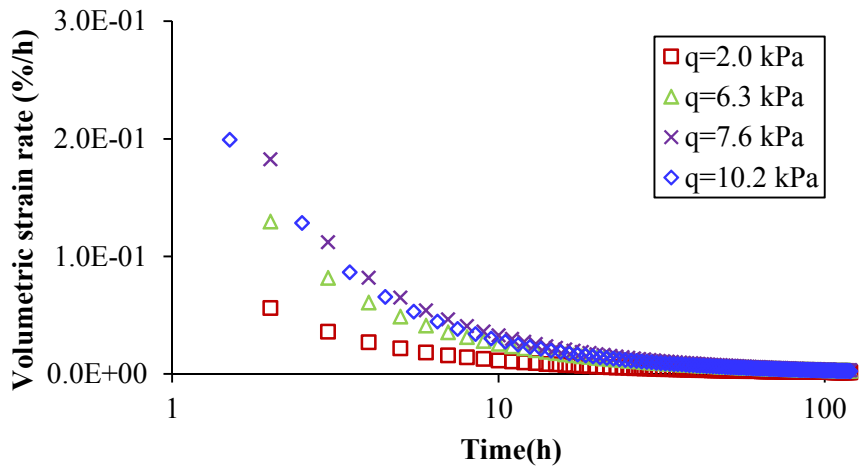
Figure 4. Volumetric strain rate – time response at different deviator stresses.
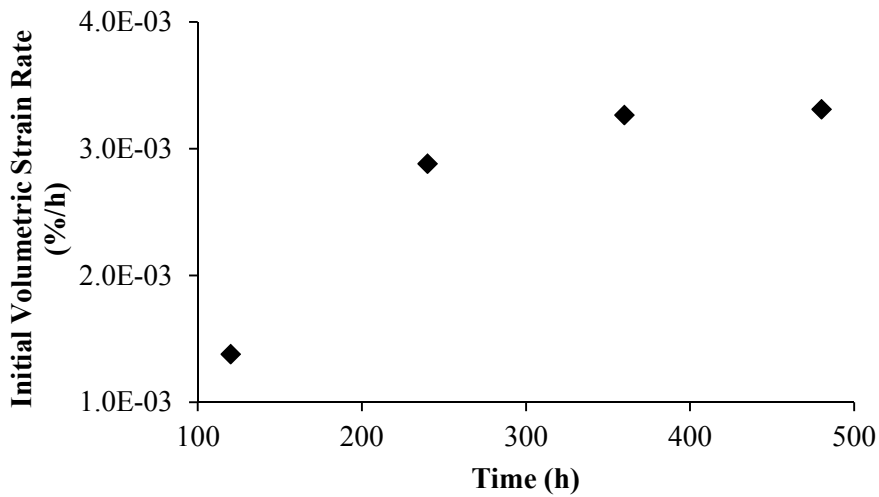

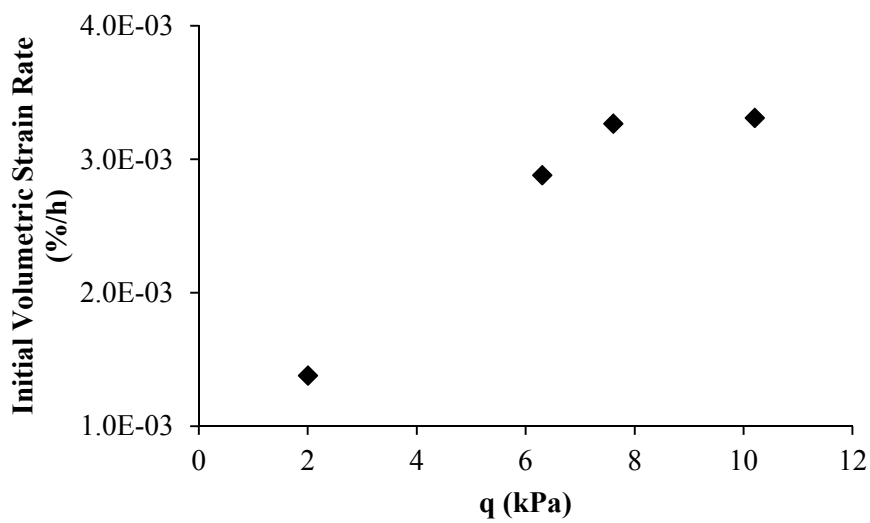**Figure 5.** Evolution of initial volumetric strain rate with time.

Figure 6. Stress-level dependency of the initial volumetric strain rate.

4. Conclusion

A multi-stage triaxial creep test was performed on the re-compacted London Clay specimen in order to explore the variations of $\dot{v}_0$ with stress level and time. Although the volumetric strain – time and volumetric strain rate – time responses were found to be in good agreement with the literature, the observed time- and stress-level-dependency of the $\dot{v}_0$ were found to be in contradiction with the general assumption of $\dot{v}_0$ as a material constant. Nevertheless, the findings of this work may not be generalised at this stage and could be limited to the studied material and mode of sample preparation. Given the fact that complicated mechanics of the long-term behaviour of soft natural soils is almost certainly behind the progressive (creep) failure of geo-structures found on these soils, further studies are required to investigate the variations of $\dot{v}_0$ over wider ranges of stress states (p, q), strains, and timescales. Research on further classification of this parameter based on additional experimental investigations is currently underway in The Nottingham Centre for Geomechanics at the University of Nottingham.

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