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Unload-reload cycling effects on the compression and swelling response of a reconstituted dredged soft marine deposit

Effets du cycle de déchargement-rechargement sur la réponse de compression et de gonflement d'un dépôt marin mou dragué reconstitué.

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ABSTRACT: Recent reclamation projects have adopted heterogeneous excavated and dredged fill material along with soil improvement techniques such as PVDs and surcharging. As such, it is necessary to fully understand the primary and secondary behaviours of the soils during loading, unloading, and reloading stages over a range of stresses corresponding to stresses prior to, during and after the soil improvement works. However, commercial oedometer lab testing typically applies a fixed loading regime that fails to capture the varying unload-reload response of the soils. Oedometer tests were conducted on a reconstituted dredged soil to investigate the effect of multi-stage unload-reload cycles at successively increasing maximum stresses against individual tests where only a single cycle was carried out. The observed response during primary compression, swelling and secondary behaviour showed no influence from the additional preceding time and stress history on the subsequent loading increments in the multi cycle test as compared to the single cycle tests. The primary and secondary unload-reload response exhibited a dependence on the OCR and maximum stress for each cycle, supporting the advantage in adopting a multi-stage approach over a standard single cycle test.

RÉSUMÉ : Récemment, les projets de comblement utilisent des sols hétérogènes provenant des excavations et dragages, et l'amélioration du sol s'effectue à travers des méthodes de surcharge. Cela nécessite une compréhension du comportement primaire et secondaire pendant le chargement, déchargement et rechargement, sur une large série de contraintes qui correspondent aux contraintes imposées par les travaux d'amélioration de sol. Pour ces projets, les essais œdométriques commerciaux adoptent généralement un chargement fixe et ne peuvent ainsi mesurer la réponse variable de décharge-recharge des sols. Cette étude présente une analyse des essaies œdométriques qui ont été entrepris sur des déblais de draguage reconstitués en laboratoire. La combinaison de plusieurs cycles de décharge-recharge à des contraintes maximales croissantes et successives dans un seul essai est comparé à des essais individuels de contraintes singulières. La réponse observée pendant la compression primaire, le gonflement et la consolidation secondaire indique aucune influence de l'accumulation du temps précédent ni de l'histoire des contraintes sur les chargements suivants dans les essais multi-cycles, par rapport aux essais à contraintes singulières. La réponse de déchargement-rechargement primaire et secondaire semble également dépendre de la ROC et de la contrainte maximale par cycle, ce qui démontre l'avantage des essais multi-cycles sur une large échelle de contraintes.

KEYWORDS: oedometer; compressibility; swelling; creep; unload-reload

1 INTRODUCTION.

With the general decreasing resources and geo-political restrictions of suitable sand material for land reclamation use, many countries such as Singapore are utilising more sustainable alternative materials to generate land area for commercial and infrastructural developments. Some 4of the alternatives include waste excavated materials from construction projects and dredged material from surrounding areas. Such material sources inextricably result in a heterogeneous soil matrix of a mixture of gravels, sands, silts and clays. The absolute and differential compressibility of these materials as in-fill in the short and long term are more concerning than the preferred sand in-fill. Typically, the materials from the construction waste source range from being partially to fully remoulded due to the excavation and transportation processes. In contrast, the dredged marine material used becomes fully reconstituted before being placed within the fill area. As such it is important to understand the behaviour of these heterogenous soils with their different initial states and soil structures.

Soil improvement techniques such as using prefabricated vertical drains (PVDs) and surcharging can be adopted as an approach to accelerate the consolidation-induced settlements and condition the soil for land reclamation projects. The purpose of the improvement techniques is also to reduce subsequent long-term settlements of such soils. In designing such solutions and estimating the settlements it is necessary to fully understand the primary and secondary responses of the soils in loading, unloading and reloading; it is generally accepted that soil behaviour varies with stress level and state (i.e., normal or overconsolidated) in these loading conditions. This is achieved through a large suite of laboratory testing. However, for such projects, commercial laboratories typically adopt a fixed loading regime in oedometer testing that often lacks unload-reload cycles, as standard, and therefore fail to capture the response expected of the soil relative to its overconsolidation and maximum stress, σ'_{vmax}. Hence, it is imperative to examine the true unload-reload response at representative stresses and states to that expected in the field in both the short and long-term time spans.

In this study, oedometer tests were conducted as part of larger study on a reconstituted dredged soil from Singapore to investigate the effect of combining multi-stage unload-reload cycles at successively increasing maximum stresses. The results from this test were compared against individual tests where only single cycles were carried out after reaching each of the respective maximum stresses. The aim was to investigate what effect, if any, was observable from the combination of the multiple cycling history at three different σ'_{vmax} and additional accumulated duration on the primary and secondary indices against a single cycle loading scheme at the equivalent σ'_{vmax} values.

2 BACKGROUND

Many researchers have made key observations through laboratory and the field studies on the different behaviour of natural, reconstituted and remoulded soils during and after the consolidation process. Several publications have documented the difference in behaviour of natural undisturbed stiff and soft soils against the reconstituted equivalent, owing to soil structure developed through diagenetic processes during deposition and post-depositional processes for the former soil types (e.g., Skempton and Northey, 1952; Leroueil et al, 1979; Burland, 1990; Schmertmann, 1991; Cotecchia and Chandler, 2000). It has become common practice to refer to reconstituted soils, particularly clays, when assessing the effect of structure on the mechanical behaviour of natural sedimentary clays (e.g Burland, 1990). A framework based on two key mechanisms, the mechanical effect and the physico-chemical effect, has been developed to describe the volumetric response of fine-grained soils, in particular clays. The mechanical effect refers to compressibility which is controlled by shearing resistance at the near contact points between particles (in which volume changes occur by shear displacements and/or sliding between particles) (Leonards and Altschaeffl, 1964), while the physico-chemical effect refers to compressibility which is controlled by long-range electrical repulsive forces between the particles (Bolt, 1956). The relative influence of each mechanism on loading, unloading and reloading has been investigated for a range of clays with respect to mineralogical composition (Olson and Mesri, 1970; Sridharan and Rao, 1973).

Skempton (1970) presented important data showing the linear response in the sedimentation compression curves (e-log σ'_v) of normally consolidated natural clays consolidated by gravitational compaction. In contrast, Burland (1990) showed that for reconstituted natural clays (thoroughly mixed at a water content greater than the liquid limit) the compression curves during virgin loading showed an upward concave shape suggesting the non-linearity of the compression index over a wide range of stresses. The rate of secondary compression was proposed by Mesri and Castro (1987) to directly correlate to the magnitude and behaviour of the compression index with consolidation pressure within the full stress range (compression and recompression) for a variety of sands, silts and clays.

Several authors have investigated and observed the response of primary and secondary compression and swelling with overconsolidation ratio (OCR), preconsolidation stress, the number of repeated static unload-reload cycles within a specific stress range and the unloading ratio of the cycle (ratio between σ'_{vmax} and σ'_{vmin} prior to and during the cycle, respectively.

The reduction of secondary compression in soft soils due to surcharging and the reappearance of compressive creep after unloading has been investigated (Ladd, 1971; Mesri and Feng, 1991; Conroy et al, 2010; Feng, 2013), where the magnitude of post-surcharge secondary response was correlated to the surcharge ratio, R_s =OCR-1, induced in the soil.

Cui et al (2013) observed that the unloading slope of natural stiff clays increased with maximum pressure σ'_{vmax}, attributing changes to the soil microstructure on unloading-reloading using the framework of competing mechanical and physico-chemical mechanisms. Similar findings were presented by Habibbeygi and Nikraz (2018) on the swelling and recompression indices, C_s and C_r for soft reconstituted clays; a reduction in the hysteresis of unload-reload loops for low σ'_{vmax} values was pointed out.

Prakash and Sridharan (2008) analysed the effects of applying repeated static unloading-reloading cycles on undisturbed and remoulded clayey soils, observing that the magnitude of the unload-reload responses reached a near equilibrium state after repeated cycles. While the magnitude and nature of variation in the soil compression and rebound differed distinctly between the undisturbed and remoulded states, they converged similarly to this equilibrium state after repeated cycles.

Butterfield (2011) proposed a model in which the slope of the reloading line in clayey soils depends solely on the unloading ratio used in the oedometer test (the ratio of σ'_{vmax} to the σ'_v value at which reloading begins). This deformation model was validated against oedometer tests conducted on natural and reconstituted clays.

Suddeepong et al (2014) proposed an improvement to Butterfield (2011) oedometer soil model. The authors similarly observed a gradual reduction and final equilibrium state in the soil unload-reload response with repeated U-R cycles. This was observed to not just apply to full U-R cycles (as standard), but also intermediate or partial U-R cycles (i.e., where the soil is not reloaded back to σ'_{vmax}).

3 SAMPLE PREPARATION AND TEST DETAILS

3.1 *Soil description and sample preparation*

A sample of soft clayey silt was obtained from dredging operations in Singapore. Owing to the processes in this operation the sample was collected in a reconstituted state. Fig. 1 shows the particle size distribution of the parent soil obtained. The Atterberg limits, particle density, soil constituents and activity are outlined in Table 1.

For the series of oedometer tests conducted in this study, the soil was prepared to a slurry at 1.5 times the liquid limit of the soil. The five oedometer samples were then preconsolidated incrementally in a large consolidometer to 50 kPa at loading increment durations and ratios equal to unity before being unloaded and carefully transferred to the main oedometer testing rings. This procedure enabled all five of the samples tested in the oedometer to start from very similar water contents and initial void ratios to enable a more direct comparison between each other.

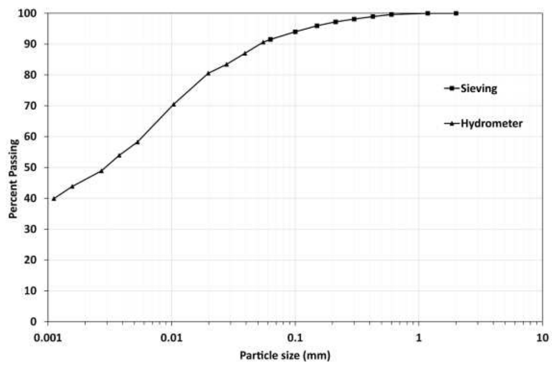

Figure 1. Particle size distribution (PSD)

3.2 *Testing details*

The five tests were conducted using conventional oedometer cells with 70mm diameter sample rings at an initial sample height of 20mm. The tests were carried out in automatic consolidation frames by VJTech using CLISP studio software.

Table 2 describes the loading regime adopted for the four baseline tests which either had no unload-reload (U-R) cycles (T0) or single U-R cycles which were initiated after loading to σ'_{vmax} of 150 kPa (T1), 300 kPa (T2) and 600 kPa (T3). These baselines tests served as comparators against T4 with three cycles, each initiated successively from σ'_{vmax} of 150 kPa, 300 kPa and 600 kPa. The compression curves from the 5 tests showing the loading, unloading, and reloading vertical increment pressure-void ratio responses are plotted in Fig. 2. Each loading and unloading increments were maintained for 24 hours.

4 RESULTS & DISCUSSION

4.1 *Global indices (C_c and C_{ur})*

Fig. 2 presents the compression curves for the various consolidation tests, where the global compression indices compared are indicated. These include the slope of the Virgin Compression Line (VCL), denoted as C_c and the slopes of the Swelling-Recompression line (SRL) for U-R cycles beginning at 150kPa, 300kPa, and 600kPa, denoted as C_{ur1}, C_{ur2}, and C_{ur3}, respectively. The values of these global compression indices for each test are shown in Table 3. The legend in Fig. 2 is structured by *Test ID-Number of U-R cycles- σ'_{vmax}* (before each cycle).

Table 1. Summary of soil index properties and constituents

w_L (%)	w_P (%)	I_p (%)	Activity	Gs	Sand: Silt: Clay (%)
60.8	25.1	35.7	0.81	2.73	8.5: 47.6: 43.9

Table 2. Details of test ID, loading increments, unload-reload cycles references and total test duration of conducted oedometer tests

Test ID	*U-R cycle ref*	Pressure applied (kPa) ***(unload-reload cycle pressures)***	Test duration (days)
T0	-	18.8,37.5,75,150,300,600,1200	7
T1	1	18.8, 37.5, 75, ***150, 75,37.5,18.8,9.4,18.8,37.5,75, 150*** 300, 600,1200	15
T2	2	18.8, 37.5, 75, 150 **300, 150, 75,37.5,18.8,37.5,75, 150, 300** 600, 1200	15
T3	3	18.8, 37.5, 75, 150, 300 **600, 300, 150, 75,37.5,75, 150, 300, 600** 1200	15
T4	 1 2 3	18.8, 37.5, 75, **150, 75,37.5,18.8,9.4,18.8,37.5,75, 150** **300, 150, 75,37.5,18.8,37.5,75, 150, 300** **600, 300, 150, 75,37.5,75, 150, 300, 600** 1200	31

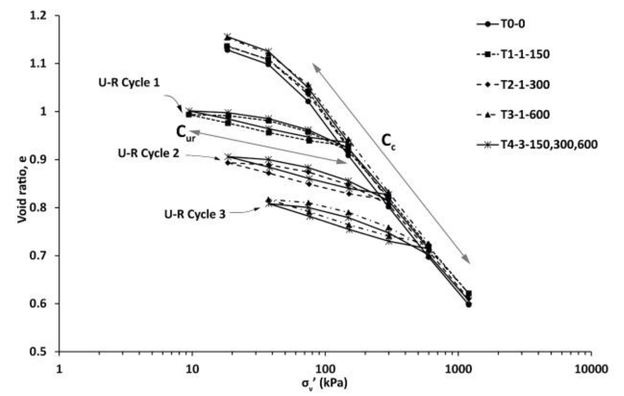

Figure 2. e-log σ_v' response for tests T0-T4)

Table 3. Summary of global C_c and C_{ur} values (tests T0-T4)

C_c (global)			C_{ur} (global)			
No cycle	Single cycle	Multi cycle	Cycle ref.	σ'_{vmax} (kPa)	Single cycle	Multi cycle
0.351 *(T0)*	0.348 *(T1)*	0.367 *(T4)*	1	150	0.061 *(T1)*	0.063 *(T4)*
	0.354 *(T2)*		2	300	0.071 *(T2)*	0.074 *(T4)*
	0.360 *(T3)*		3	600	0.084 *(T3)*	0.087 *(T4)*

The global index values C_c and C_{ur} for U-R cycles 1, 2 and 3 for test T4 were observed to remain consistent with their corresponding values from T0, T1, T2 & T3.

The slope of the SRL was observed to consistently increase with increasing σ'_{vmax} for both T4 and the corresponding single-cycle tests (i.e. $C_{ur1} < C_{ur2} < C_{ur3}$), which is in agreement with other published findings (Cui et al, 2013; Habibbeygi and Nikraz (2019); Zhang et al, 2020). Olson and Mesri (1970) noted that the relative influence of the mechanical and physico-chemical effect on clay compressibility depends heavily on inter-particle contact angle. As the soil undergoes further virgin compression, the soil structure experiences large pore collapse and a reduction in the size distribution and geometric complexity of the pore shapes (Zhang et al, 2020). Cotecchia et al (2020) noted for both natural and reconstituted soils that with increasing stress post-yield the fabric rearrangement that occurs gives rise to a regular alternation of stacks of well-orientated particles with flocculated honeycomb-like fabric structures. In contrast, Cui et al (2013) suggested that post-yield loading results in increasingly orientated particles. Le et al (2011) noted that the reduction in the contact angle due to increasing fabric orientation results in the increasing dominance of the physico-chemical interaction between clay particles and adsorbed water. Thus, a more significant swelling response would be expected upon unloading as the more oriented particles experience larger repulsion forces between each other, as seen in the values of C_{ur1}, C_{ur2}, and C_{ur3} in Fig. 2 and Table 3.

Many of the previously mentioned studies have focused on the soil structure behaviour for near-pure clays. However, for the sample tested, as indicated in Table 1, the small presence of sand (8.5%) and the larger quantity of silt (47.6%) as compared to the clay content (43.9%) requires an examination of whether the observed behaviour is transitional or clay dominant. Shipton and Coop (2012) typified transitional behaviour by non-convergent compression paths and critical state lines that are non-unique and depend on the initial sample density (which are otherwise present for clean coarse-grained soils and clays). Nocilla et al (2006) observed that well-graded clayey silts from the Po River embankments which were reconstituted with controlled clay contents (3.5-45%) showed possible transitional behaviour for clay contents up to 20%, but not at 45% at which the response is suggested to become clay dominant. With this and observations of the tested soil's PSD, it is possible to suggest that the soil might also exhibit non-transitional clay-dominant behaviour. This would be in line with the observed varying unload-reload response with stress associated with the physico-chemical mechanism for clays, introduced by Bolt (1956). In a recent holistic review of the framework for transitional behaviour in soils, Mousa and Youssef (2021) identified the large number of both quantitative factors and qualitative conditions, not limited to plasticity index, clay and fines content and activity, intergranular void ratio, yield stress, separation between and convergence to CSL and NCL, inter-grain silt fraction contacts, mineralogy, stress history and drainage conditions. The authors concluded that significant research is still required to understand the mechanisms defining the behaviour of transitional soils.

4.2 *Local virgin loading response*

Fig. 3 shows the local compression index values C_c ($\Delta e/\Delta \log \sigma'_v$) for tests T0 to T4 in virgin loading. A downward trend was observed in C_c with increasing stress in T0 (with no U-R cycles), which agrees with findings by Burland (1990) on various reconstituted clays with a wide range of plasticities. This is generally accepted to persist as a soil is loaded to higher consolidation stresses along the VCL, which becomes gradually asymptotic approaching a stable void ratio. Similar magnitudes of changes in C_c with increasing stress, both before and after the U-R cycles, were also observed for the single cycle tests (T1-T3) and the multi-cycle test (T4). This would suggest that collapse of the large pores that occurs during virgin compression (Delage and Lefebvre, 1984; Cotecchia, 2020; Zhang et al, 2020) leads to irrecoverable volume changes that dominate over those due to microstructure changes that occur during the U-R phase (Cui et al, 2013; Zhang et al, 2020). The local C_c values for test T4 remained consistent with test T1 despite having two additional U-R cycles at σ'_{vmax} values of 300kPa and 600kPa, indicating that the structural changes due to the added U-R stress history in T4 is superseded once the soil is compressed further along the VCL.

For tests T1 to T4, the local C_c value obtained between σ'_{vmax} and the subsequent increment after the U-R cycle consistently showed a drop as compared to the value prior to the U-R cycle. This again can be explained by the irreversible volume changes in the microstructure during cycling, resulting in a lower void ratio. In the stages after, the local C_c value rebounded to that observed before the cycle. Butterfield (2011) described a similar behaviour in his improved model of soil response.

Fig. 4 presents the local secondary compression index values C_α ($\Delta e/\Delta \log t$) for tests T0 to T4 in virgin loading, where the C_α values were observed to fall within a narrow range of 0.7 ± 0.1%. This is in line with several studies conducted on soft soils (Graham et al, 1983; Jiang et al, 2020; Zhang et al, 2020), where C_α is noted to stabilise with pressures past the pre-consolidation or yield stress i.e., on virgin compression.

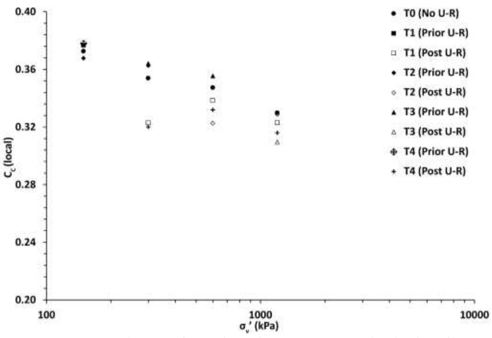

Figure 3. Comparison of C_c (local) vs. σ_v' on virgin loading (tests T0-T4)

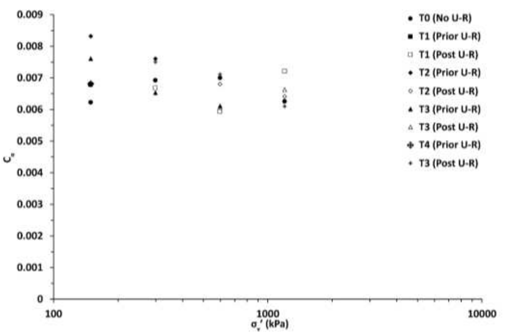

Figure 4. Comparison of C_α vs σ_v' on virgin loading (tests T0-T4)

The microstructure of undisturbed natural clays has been found to be far more complex than its reconstituted counterpart. This has been attributed to diagenesis which increases bonding of the clay particles and increases the local randomness of the clay particle arrangement (Cotecchia et al, 2020). As such, greater relative movement occurs between undisturbed clay particles resulting in greater secondary compression (Mitchell, 1956). The development of additional structural resistance has also been observed for clays that experience an ageing effect under sustained loading and secondary compression (Bjerrum, 1967; Mesri et al, 1975; Graham et al, 1983). It is important to note that this ageing effect is not equivalent to the increase in total accumulated time spent under secondary compression in test T4 (at every additional U-R loading stage in which the soil is allowed to creep after primary consolidation within the 1-day loading duration). In this case, the soil is not provided sufficient time to develop additional bonding and structural reconfiguration. Any possible effects of accumulated microstructural changes during each additional U-R cycle were overcome as the soil was loaded back down the VCL, hence no changes were observed in C_c or C_α against T0-T4.

4.3 *Local unloading response*

The unloading of soils results in a change in the soil structure over time with the dissipation of excess pore pressure during primary swelling (defined by the swelling index, C_s) and under constant effective stress in secondary swelling. Mesri et al (1978) attributed the occurrence of secondary swelling ($C_{\alpha,s}$) to several interdependent effects, including time-dependent microstructural readjustments, progressive breakdown of diagenetic bonds, progressive development of structural discontinuities and chemical changes. The secondary swelling response is more pronounced in clays than silts or sands due to the additional physico-chemical repulsive forces that occur with such soils on the reduction of effective stress.

The local swelling index values C_s for tests T1 to T4 on unloading are presented against $\log_{10}$ OCR in Fig. 5. A dependence on OCR was observed, where C_s increased up to OCR = 8 before levelling off and slightly decreasing at higher values. Similar observations were made by Mesri et al (1978) on various reconstituted clays; it was suggested that this behaviour was linked to both OCR and possible oedometer ring side friction.

Mesri et al (1978) observed a varying influence of σ'_{vmax} on C_s across their isotropic and oedometric tests, noting its effect was dependent on the soil composition and OCR. For the given single reconstituted clayey silt, the influence of σ'_{vmax} was apparent; near parallel curves were observed for OCR > 2 (i.e., subsequent stages after the first load reversal). It is also clear that the magnitude of C_s increases with higher σ'_{vmax} (indicated by the upward arrow in Fig. 5). A similar response in local C_s with σ'_{vmax} was also observed by Cotecchia et al (2020) for natural and reconstituted clays. The behaviour with local C_s fits with the general response in the global C_{ur} index from the best-fit of the unload-reload response in Fig. 2 and Table 3.

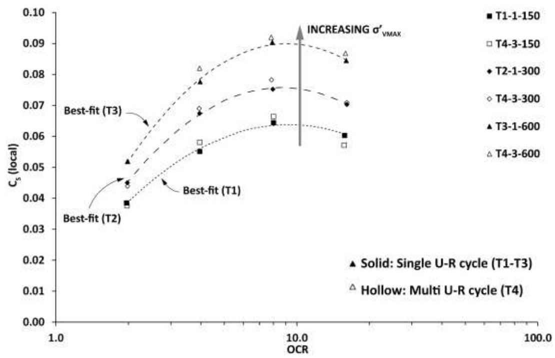

Figure 5. Comparison of C_s (local) vs OCR on unloading (tests T1-T4)

Building on observations by Mesri and Godlewski (1977), Mesri et al (1978) proposed that $C_{\alpha,s}$ would be expected to increase over time. Later studies conducted by several researchers on post-surcharge removal response of soils showed a differing evolution of $C_{\alpha,s}$ with time (e.g. Feng, 1991; Mesri and Feng, 1991; Ng, 1998; Tanaka et al, 2014). Vergote (2020) summarised that $C_{\alpha,s}$ gradually reduces before the appearance of secondary compression (typically denoted as C_α') occurs; the time at which secondary swelling concludes and secondary re-compression reappears was found to be highly dependent on OCR for a range of soils. Vergote (2020) noted that for lab testing at high OCR, a typical minimum period of 7 days is required to observe the re-compressive creep on unloading. From the 24-hour loading increment durations used throughout this study, secondary compression was not observed within the 1-2 log time cycles from which $C_{\alpha,s}$ was measured after the end of primary swelling; this response is being further investigated with respect to the multiple versus single cycle tests under longer and varied loading durations.

Varying responses were observed by Mesri et al (1978) in the ratio of secondary to primary swelling $C_{\alpha,s}/C_s$ against $\log_{10}$ OCR for different reconstituted soils, ranging from linear to downward concave correlations with increasing OCR. It was noted from their oedometer tests that $C_{\alpha,s}/C_s$ at a given OCR decreased with increasing σ'_{vmax}. This general trend was also observed for tests T1 to T4 in Fig. 6 (indicated by the large arrow in Fig. 6) where a nonlinear response is noted in $C_{\alpha,s}/C_s$-$\log_{10}$OCR. It can be seen that the sensitivity of $C_{\alpha,s}/C_s$ to σ'_{vmax} is greater at higher OCR, resulting in a progressively increasing difference/spread in the values between T1 to T3 at a given OCR.

Fig. 5 shows that the values of C_s in each of the three successive unload paths in T4 were very similar to their corresponding points in T1, T2, and T3. This further corroborates the negligible effects from previously accumulated strains and testing duration for a multi-cycle test (T4) against the conventional single cycle tests. For $C_{\alpha,s}/C_s$ (Fig. 6), the variation between the T1, T2 or T3 values against T4 slightly increased with increasing OCR, although no obvious trend was observed in this discrepancy. This is important given the apparent dependence of C_s and $C_{\alpha,s}/C_s$ with OCR and σ'_{vmax} for the tested reconstituted soil; further sensitivity may be observed in natural soils owing to the greater extent of structure established.

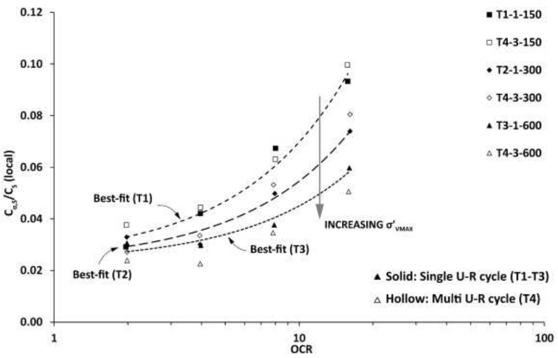

Figure 6. Comparison of $C_{\alpha,s}/C_s$ (local) vs OCR on unloading (tests T1-T4)

4.4 *Local reloading response*

The local recompression index values on reloading, C_r, for tests T1 to T4 are presented against the $\log_{10}$ OCR in Fig. 7. A clear downward linear response was consistently observed for each test (i.e. C_r increases from OCR = 8 to 1 as the soil is reloaded back toward the VCL). This trend agrees with Cui et al's (2013) proposed reloading mechanism in natural clays entailing the competition between mechanical and physico-chemical effects. When the external stress is lower than repulsive forces related to the physico-chemical effect, these stresses are balanced by the repulsive forces, leading to a small volume decrease. Once the external stresses exceed these repulsive forces, the mechanical effect dominates resulting in a larger volume decrease. The consistency in the variation of C_r with respect to $\log_{10}$ OCR is also in line with Butterfield's (2011) oedometer soil model, who noted that the reloading path remains geometrically similar for a given unloading ratio (fixed at $\sigma'_{vmax}/\sigma'_{vmin}$ = 16 for all U-R cycles in T1-T4).

With each increasing σ'_{vmax} value, the linear relationship observed in the local C_r-$\log_{10}$OCR also increased (as indicated by the arrow in Fig. 7). This behaviour was more pronounced at the intermediate OCRs; it was observed that stages with a reversal of loading (from unloading to reloading at OCR = 8 and from reloading to virgin loading at OCR = 1) have an influence on the range of local C_r at these stages compared to those stages in between. However, the change in C_r between the varying σ'_{vmax} values was less significant compared to the unloading response. This might suggest that the influence of the physico-chemical mechanism, which gives rise to an increase in C_s with increasing σ'_{vmax} due to larger interparticle repulsion forces, is less apparent compared to mechanical effects on reloading.

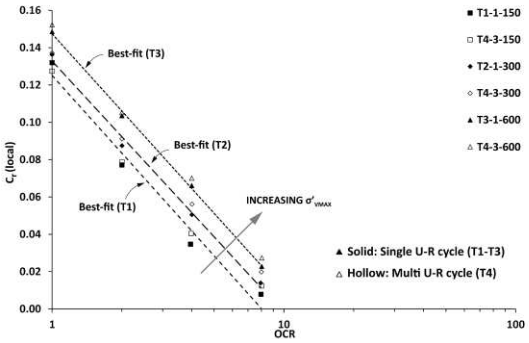

Figure 7. Comparison of C_r(local) vs OCR on reloading (tests T1-T4)

Fig. 8 shows the secondary compression index values on reloading C_α' for tests T1 to T4. A similar downward trend was observed against $\log_{10}$OCR, within a consistent band of values that significantly increase at OCR = 1. This is expected and consistent with studies investigating the reduction of secondary compression by inducing overconsolidation in soft soils through surcharging (Ladd, 1971; Mesri and Feng, 1991; Conroy et al, 2010; Feng, 2013), where secondary compression has been shown to reduce significantly with an increase in OCR. The relative consistency in C_α' values between all the tests suggests that OCR has more influence than σ'_{vmax} on secondary compression upon reloading. This contrasts with the responses observed in primary (C_s) and secondary swelling ($C_{\alpha,s}$) as well primary compression on reloading (C_r), which appear to be influenced by σ'_{vmax} to varying degrees. Many theories have been proposed to date on the mechanism of secondary compression in soft clayey soils which largely incorporate the role of clay mineralogy and deformation of both the soil macro and microstructure (Taylor and Merchant, 1940; Taylor, 1942; Mitchell, 1956; De Jong and Verrujit, 1965; Kuhn and Mitchell, 1993). It has only become more evident that the mechanism behind secondary compression is entirely unique and differs not only from the primary consolidation but also secondary swelling process; the latter cannot therefore be considered as simply the inverse of compressive creep deformation.

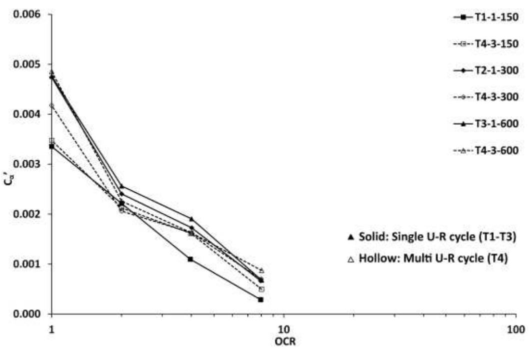

Figure 8. Comparison of C_α' vs OCR on reloading (tests T1-T4)

The values of both C_r and C_α' for T4 at each σ'_{vmax} value (150, 300, and 600 kPa) remained largely consistent with the values of the equivalent single cycle tests (T1 at σ'_{vmax} = 150 kPa, T2 at σ'_{vmax} = 300 kPa, and T3 at σ'_{vmax} = 150 kPa). This again would suggest that the influence of any accumulated microstructural changes due to additional U-R cycles is minimal compared to the large pore collapse that occurs in virgin loading for a fixed loading duration of 1 day. As such, the soil structure in T4 was comparable to T2 and T3 at σ'_{vmax} = 300kPa and 600kPa, respectively, regardless of its preceding U-R stress and time history.

5 CONCLUSIONS

A series of oedometer tests were conducted on a reconstituted dredged clayey silt to assess the variance in primary and secondary responses on loading, unloading and reloading at various stresses. On unloading, the magnitude of primary swelling C_s as well as the ratio of secondary to primary swelling $C_{\alpha,s}/C_s$ were observed to be significantly influenced by both OCR and the maximum stress before unloading σ'_{vmax}. On reloading, OCR was observed to considerably affect both the primary and secondary recompression indices C_r and C_α', while the observed influence of σ'_{vmax} was more prominent with C_r.

In order to correlate the observed sensitivity of the unloading and reloading response with OCR and σ'_{vmax}, it is important to assess the overconsolidated time-settlement behaviour of soil based on the appropriate stress paths and history expected in field conditions. It was shown that it is feasible to estimate this response for a given soil in the field at various depths with differing σ'_{vmax} history by conducting a single test consisting of multiple U-R cycles at successive maximum stresses, where minimal influence was observed from the accumulated stress and time history due to the additional cycles on both global and local indices in the primary and secondary responses during loading, unloading and reloading.

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