Post Preloading Creep Properties of Highly Compressible Harbor Marine Sediments

Francisucs Xaverius Toha

Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung
CIBE Building, 5th Floor, Room 0511, Jalan Ganesha 10, Bandung 40132, Indonesia
E-mail: fxtoha@ftsl.itb.ac.id

Abstract. A laboratory experimental research in creep behavior of soft clay marine sediments was done to investigate creep strain under reloading. A total of 52 oedometer tests were carried out with 16 slurry sediment samples subjected to cycles of unloading at preload removal pressure and reloading to higher design pressures. Common practice as well as more recent advanced methods of creep deformation analysis were used to refine the predictions. The study indicates that although preloading substantially reduces post construction creep, the analysis is very sensitive to creep indices at slight overconsolidation and the resulting creep may not be negligible at previously established limits of primary to secondary compression ratios.

Keywords: *creep index; marine sediment; post construction creep; reloading creep index; time at creep initiation.*

1 Introduction

Recent developments of port projects for large vessels requiring deeper water depths and high container yard surcharge loads in Indonesia face major challenges in dealing with soft clay marine sediments. Dredging of the seabed for navigational channels yields large quantities of contaminated material unsuitable by law for outside dumping. The dredged material, containing mostly clay or silty clay, is used for container yard reclamation sites. The soft clays are highly compressible, hence, even after elimination of consolidation settlements by preloading, post construction creep may still be large. When subjected to yard design loads, the reloading after surcharge removal will occur in an overconsolidated state of the clay. Unacceptable large creep deformation may be enhanced by the presence of prefabricated vertical drains (PVD). Results of previous studies on reduction of post construction creep by surcharging were applied in our analysis to provide more detailed insight and refinements.

Presence of continued deformation beyond Terzaghi's [1] consolidation was first observed in the field by Buisman [2]. This deformation at negligible pore pressure dissipation and effective stress change is defined as secondary compression or creep in this paper. Early methods of creep assessment were

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done by assuming creep occurring after consolidation is completed. However, subsequent laboratory and field research, among others by Taylor [3,4], Šuklje [5], Bjerrum [6], Janbu [7], Larsson and Mattsson [8], and Leroueil [9] indicated that creep also occurs during primary consolidation. A detailed and exhaustive overview of creep settlement studies can be found in Feng's [10] dissertation.

This research focused on laboratory investigations on creep parameters of selected marine soft clays from Cirebon, Sorong and Kalibaru port locations in Indonesia. All the dredged clays at the three sites were and will be used for reclamation, with thicknesses between a few meters to 12 meters. Creep analysis was done beyond the most recent advancements with constant surcharge after preload removal, extending into higher stresses representing container yard design pressures. Additional insight in the effect of creep index parameters to creep estimates was instigated and reclassification of negligible creep limits based on primary to secondary compression ratios were pointed out.

2 Current Practice in Creep Settlement Analysis

In common practice, creep settlement is analyzed as a subsequent deformation occurring after primary consolidation at the time when pore pressures are dissipated and effective stress remains constant. More recent research results indicate that creep settlement occurs at the same time as consolidation settlement. The research reported here follows the more recent concepts in creep analysis, where creep is considered a time dependent behavior.

Using Mesri and Feng's [11] definition and notations, the magnitude of secondary compression or creep, S, is determined from:

$$S = \frac{C_\alpha L_o}{1+e_o} \log \frac{t}{t_p} \tag{1}$$

where C_α is the coefficient of secondary compression or the creep index when the soil is normally consolidated; L_o is the thickness of the soil sublayer; e_o is the initial void ratio; t is the time from initiation of creep; t_p is the time to end of primary consolidation. The creep settlement, S, after preload soil improvement surcharging and preload removal, after both primary and secondary rebound times, t_{pr} and t_l, respectively, is:

$$S = \frac{C_\alpha'' L_o}{1+e_o} \log \frac{t}{t_l} \tag{2}$$

where C''_α is the secant reloading creep index. Mesri and Feng [11] recommended the use of C''_α instead, because the reloading creep index, C'_α, is not constant over time, by modifying Eq. (1) into:

$$S = \frac{C''_\alpha / C_\alpha \times C_\alpha / C_c \times C_c}{1 + e_o} L_o \log \frac{t}{t_l} \tag{3}$$

in which C_c is the compression index. Mesri and Feng [11] suggested C''_α / C_α values based on empirical results from various tests on inorganic and organic soft clays, where t/t_l was used after obtaining t_l/t_{pr} according to Mesri [12]:

$$\frac{t_l}{t_{pr}} = 100\,(OCR - 1)^{1.7} \tag{4}$$

where OCR is the overconsolidation ratio. Subsequently, using C_α and C_c values from oedometer tests, Mesri and Feng's [11] observational method is used to estimate the creep.

More recently, Wong [13] evaluated creep using strain rates, incorporating the following correlation from test results:

$$\frac{C_{\alpha\varepsilon(oc)}}{C_{\alpha\varepsilon(nc)}} = \frac{(1 - m)}{e^{(OCR-1)n}} + m \tag{5}$$

where $C_{\alpha\varepsilon(oc)} = C'_\alpha / (1 + e_o)$, is the creep strain rate for overconsolidated soils; $C_{\alpha\varepsilon(nc)} = C_\alpha / (1 + e_o)$, is the creep strain rate for normally consolidated soils; m and n are empirical constants, with m being equivalent to C_r/C_c according to Mesri and Feng [11], and C_r is the recompression index. In a more recent publication on the same issue, Yuan *et al.* [14], suggested:

$$\frac{C_{\alpha\varepsilon(oc)}}{C_{\alpha\varepsilon(nc)}} = \frac{2}{OCR^{\beta} + 1} \tag{6}$$

where β is a constant, to be determined from the data. Furthermore, using the same $C_{\alpha\varepsilon(oc)}/C_{\alpha\varepsilon(nc)}$ value for C'_α/C_α, following Buggy and Peters [15], the creep can be obtained from rewriting the given expression to:

$$S = \frac{C'_\alpha / C_\alpha \times C_\alpha / C_c \times C_c}{1 + e_o} L_o \log \frac{t}{t_S} \tag{7}$$

where t_S is the time at the start of secondary compression, determined from:

$$\log\left(\frac{t_S}{t_R}\right) = 2(OCR-1) - 0.075 \tag{8}$$

with t_R as time at preload removal.

Eqs. (1) to (8) were used in analyzing the laboratory test results without modifications to the basic equations. However, the parametric constant m in Eq. (5) turned out to be different from the suggested C_r/C_c.

3 Properties of Selected Marine Sediments

3.1 Index Properties

Three clays, originating from the seabed at Cirebon, Sorong and Kalibaru, were used in this research. All clays exhibited in-situ N_{SPT} values between 0 to 2 blows/ft. Oedometer tests were performed on undisturbed piston samples as well as on slurry sediment samples from grab dredged material. Filtering against anomalous data values that may be attributed to sampling or testing errors was done prior to the analysis. Table 1 shows relevant index properties of the clays.

Table 1 Index properties of clays.

Site	**Index Properties**				
	w (%)	***LL***	***PI***	G_s	e_o
Kalibaru	69-405%	69-147	42-105	2.51-2.73	1.8-8.9
Cirebon	102-114%	110-119	71-81	2.5-2.69	2.36-3.97
Sorong	46-63%	44-83	17-58	2.60-2.74	0.96-1.85

3.2 Consolidation Parameters

Results from 52 oedometer (consolidation) laboratory tests following ASTM D2435 Test Method A specifications were selected in this research. From these, 42 tests were done on undisturbed samples and 10 tests were done on slurry sediments. As part of a graduate study research program, details of slurry sample preparations and testing procedures were compiled in Sarifah's [16] thesis. In all the tests at least one cycle of unloading and reloading was performed around the design pressure range from 100 kPa to 640 kPa in order to obtain creep parameters of the clays after a preloading event. Most of the previous works by other authors deal with creep under sustained loading after preload removal, whereas in this research a different condition was applicable, where reloading due to high container yard load was imposed.

The compression index values, C_c, are shown in Figure 1. Test data points are compared to empirical estimates based on e_o and specific gravity, G_s, according to Rendon-Herrero [17]; as well as estimates based on liquid limit, *LL,* according to Skempton [18], and based on natural water content, w_n, according to Azzouz, *et al.* [19]. The data show that the Cirebon and Kalibaru clays have similar compressibility, whilst the Sorong clay is much less compressible.

In published earlier works, in normally consolidated state, creep parameters are related to C_c and to recompression index, C_r, in overconsolidated state.

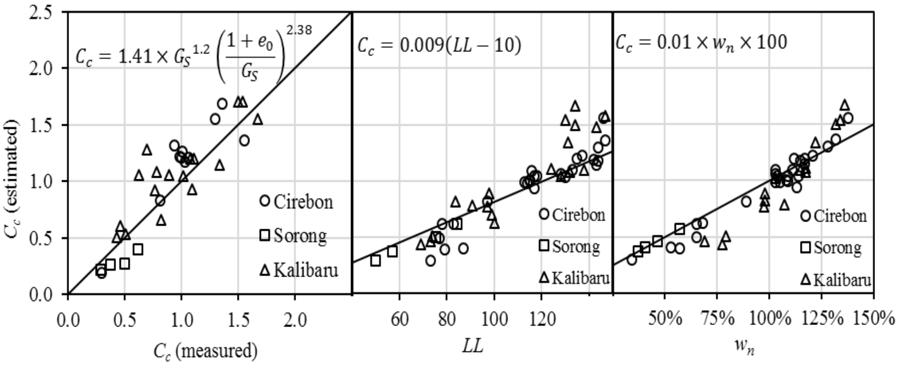

Figure 1 Compression index, Cc.

The recompression index values, C_r, are shown in Figure 2. The data suggest that C_r/C_c ratio is in the range of 0.15 to 0.25, which is common to a wide range of natural clays.

The laboratory experiments also showed that the measured C_c values remain essentially constant when the sample is normally consolidated before unloading and at reloading beyond the pre-consolidation pressure, σ'_p. The σ'_p data reveal that the samples were initially deposited by sedimentation to a normally consolidated condition, then over the time after deposition, due to creep, *OCR* values between 1 and 1.2 were achieved. Furthermore, due to sampling and testing disturbance, a few samples exhibited an *OCR* slightly less than unity. These are attributed to the test disturbance and soft nature of the seabed clays and slurry sediment samples, as it is difficult to accurately determine the point with a minimum radius in the relatively small curvature *e* - log *p* curves to determine σ'_p. In connection to creep after preloading, the laboratory data analysis with *OCR* values up to 1.5 were subject to an elaborate analysis, since for typical water depth and reclamation height, it would not be economical to consider higher *OCR* values.

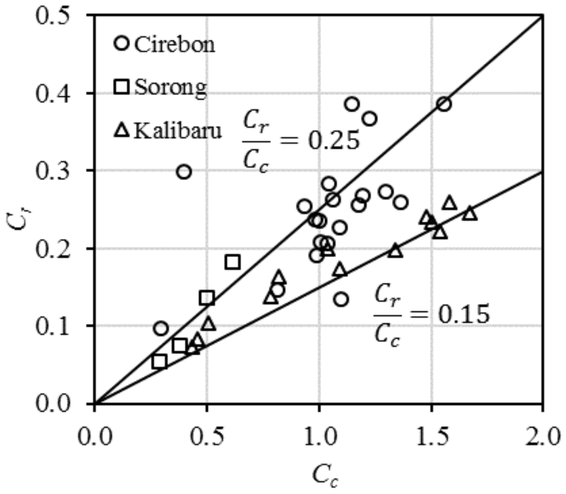

Figure 2 Recompression index, Cr.

3.3 Creep Parameters

In several past researches, efforts to minimize post construction settlement due to creep was investigated for methods with preloading in excess of the recommended design load. It has been known that the creep index, C_α, will be reduced when the clay becomes overconsolidated. In most published results the creep occurs at sustained overburden pressure after preload removal. For port projects, however, the preloaded reclamation site will be subject to reloading by container yard loads, even though the design loads usually remain below the σ'_p achieved during soil improvement. Therefore, a lot of the elaboration in this research was focused on the reduction of the creep index, C_α, at reloading after removal of preload. To obtain representative C_α values during reloading after preload removal, in addition to the load sequences of ASTM D2435, additional cycles of unloading and reloading were done within the post preloading pressure ranges as described previously.

3.3.1 Creep Index, Cα

Due to a lack of distinct breaks in most of the log time curves, Casagrande and Fadum's [20] method was not adopted; instead, the determination of creep index, C_α, was done using Taylor's [21] square root of time method. A summary of C_α values at normally consolidated condition are plotted against C_c in Figure 3. Judging from the range of C_α values between 0.01 and 0.05, according to Mesri [22], the clays in this research can be classified as having high to very high secondary compressibility.

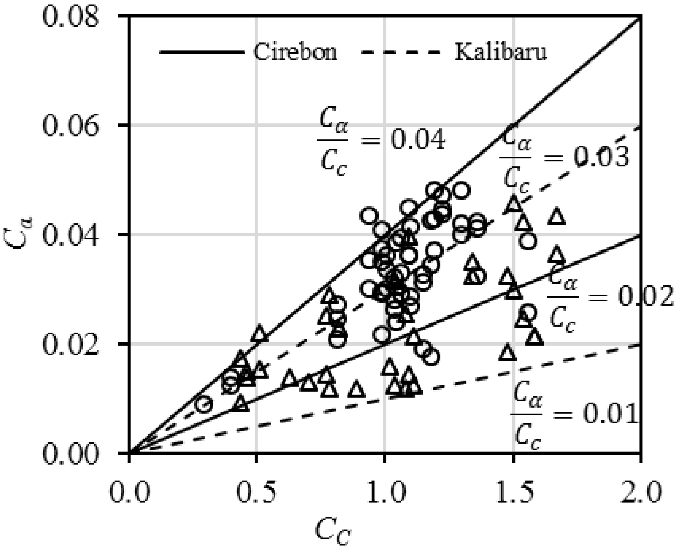

Figure 3 Creep index, Cα.

Instead of using C_α values, in connection with creep deformation analysis using the Soft Soil Creep (*SSC*) model in the PLAXIS software, Waterman and Broere [23] suggested that $(C_c - C_r)/C_\alpha$ values above 25 can be used as threshold where creep can be neglected. About 40% of the $(C_c - C_r)/C_\alpha$ values from the tests are above 25, which means that if a PLAXIS *SSC* model is used, it is anticipated for these samples that creep deformations will be small. It will be shown later in this paper that this $(C_c - C_r)/C_\alpha > 25$ criteria does not indifferently warrant small creep, as the estimate of the creep initiation time by different methods may still result in large creep for cases satisfying the criteria.

Before using Mesri and Feng's [11] Eqs. (1) to (3), it is necessary to evaluate C_α/C_c for the clays. The C_α/C_c values presented in Figure 4, are in general agreement with Mesri and Godlewski's [24], who quoted 0.025 to 0.055 ± 0.01 values for clays as well as nearshore clay and silts. However, the data in Figure 4 show a definite reduced trend of C_α/C_c with increasing σ'_v, whereas Mesri and Godlewski [24] stated that it is constant with σ'_v and t. Likewise, Wong [12] increased C_α/C_c with increasing σ'_v in his analysis of creep under sustained loads. Recently, after evaluating a large amount of additional data, Mesri and Vardhanabhuti [25] concluded that the ratio can indeed stay constant, increase and decrease with σ'_v.

This uncertain trend in the stress effect on C_α/C_c is currently still being investigated in our continuing research, where the preliminary possible contributing factors are, among others, stress increment pattern, determination of time at which creep is initiated, and the length of time the load is sustained to observe creep. In this paper, all the results came from consolidation tests in accordance to ASTM D2435 Method A, with Taylor's [21] method of interpretation.

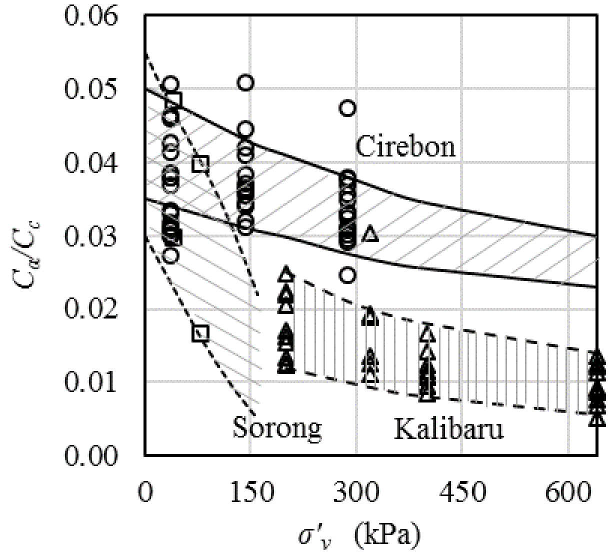

Figure 4 Ratio of Cα/Cc for normally consolidated samples.

3.3.2 Reloading Creep Index, C'α

The creep behavior due to reloading after preload removal was investigated in this research by performing cycles of unloading and reloading. At certain stages of the tests, σ'_v was reduced to $0.5\sigma'_v$. Then, after the sample was allowed to rebound for a full day, loading resumed to σ'_v again. From the deformation-time curves, primary consolidation and secondary compression as well as rebound were quantified using Taylor's [21] method. The creep index during the reloading, C'_α, is shown in Figure 5. Data of creep index at oedometer pressures below the undisturbed sample's field σ'_p were added as C'_α values in Figure 5.

Using the general curve shape after Magnan, *et al.* [26] for C_a versus σ'_v/σ'_p, the data can be plotted as shown in Figure 6. The data show a large scatter in C_a values when $\sigma'_v/\sigma'_p > 1$, i.e. when the soil is normally consolidated. At $0.75 < \sigma'_v/\sigma'_p < 1$, when the soil becomes overconsolidated with $OCR < 1.5$, C'_a drops rapidly with a wide scatter to an asymptotic value at $OCR \sim 2$, where creep can be expected to be small. This implies that accurate prediction of creep upon reloading with $1 < OCR < 1.5$ is very challenging.

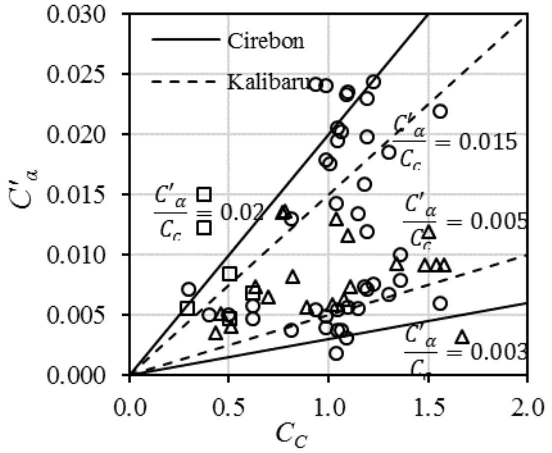

Figure 5 C'α during reloading.

In attempting to obtain more definite predictions for C'_α, the C'_α/C_α and C_r/C_c values are presented in Figure 7. It is obvious that C'_α/C_α values between 0.4 to 0.9 from samples with $OCR \leq 1.5$ do not seem to correlate well with C_r/C_c. At $OCR > 1.5$, the median C'_α/C_α value will be about 0.1. The data suggest that it is not possible to predict C'_α/C_α from C_r/C_c values.

From projects in Australia and referring to work of others, Wong [13] proposed Eq. (5) to quantify the effect of OCR to C'_α/C_α. In using Eq. (5) for his data, Wong [13] assigned $m = 0.05$ and n = 6, contrary to Mesri and Feng's [11] suggestion, where $m = C_r/C_c$. For Wong's [13] data, C_r/C_c was 0.10.

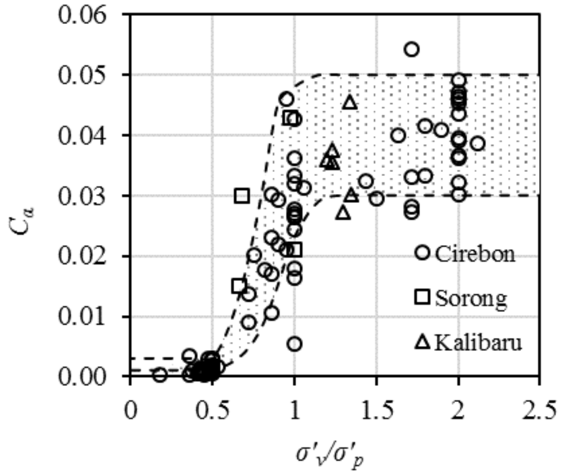

Figure 6 Effect of stress level, σ'v/σ'p to creep index, Cα.

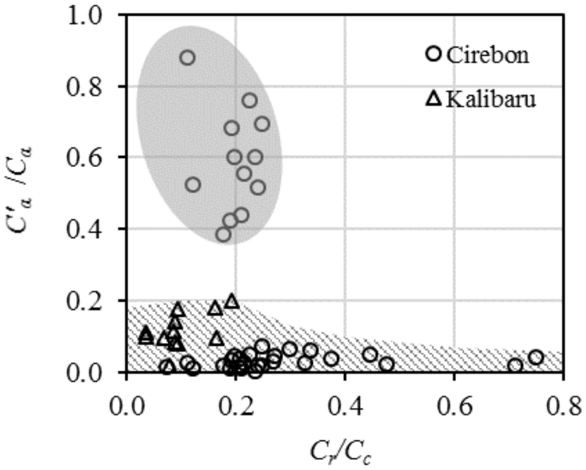

Figure 7 Creep index and compression index ratio.

From the research data plotted in Figure 8, as the C'_α/C_α at high *OCR* are much smaller than $C_r/C_c \cong 0.15$ to 0.25 in Figure 2; it would be more appropriate to use $m = C'_\alpha/C_\alpha \sim 0.02$ in addition to modifying n in Eq. (5) to (4).

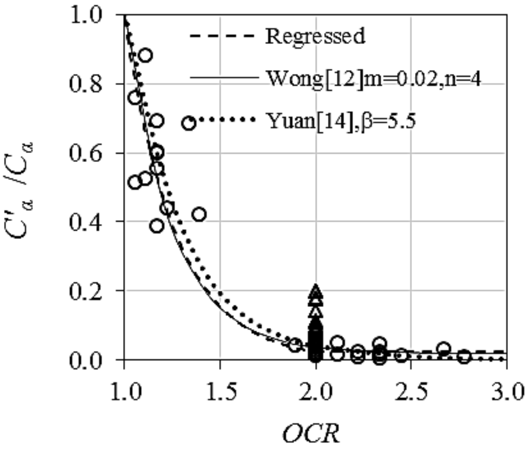

Figure 8 C'_α/C_α versus *OCR*.

An excellent agreement between the regressed data and Eq. (6) with $\beta = 5.5$, as recently proposed by Yuan [14], is established. The difference in the calculated C'_α/C_α at $OCR < 1.2$ is not significant if any of the three correlations is used, although the laboratory data scatter can amount to large deviation in creep estimates. Figure 8 also shows that the reloading creep index, C'_α, is as much as 60% lower than C_α, if $OCR > 1.2$.

4 Creep Strains

After the laboratory experiments and analysis, the results were applied to a creep deformation analysis. The Mesri's [12] observational method as well as Buggy and Peters' [15] simplified method were utilized for creep assessment. In order to exclude the effect of variable layer thickness, the creep analysis focused on the strain values, ε_c, instead of the deformation.

In the Mesri's [12] analysis, a typical prefabricated vertical drain (PVD) soil improvement was assumed. A typical PVD cross section of 100 x 4 mm, with a triangular grid spacing, S_{PVD}, between 1 and 1.5 m; a rebound coefficient of consolidation, c_{hr}, determined from unloading stages of the Kalibaru slurry samples, ranging from 200 to 8,000 m^2/year; and a measured primary rebound, t_{pr}, varying from 1.2 hours to 4.5 days were used. For *OCR* values ranging between 1.2 and 1.4, the initiation of creep or time end of secondary rebound relative to preload removal, t_l, calculated from Eq. (4), varied between 8 hours to 95 days. Subsequently, using Mesri's [12] empirical results for C''_α/C_α, for a service lifetime of 50 years and a range of $C_c/(1+e_o)$ from 0.2 to 0.35, the resulting creep strains, ε_c, for brevity shown for a range of $c_{hr}\ t/S^2$, are plotted in Figure 9. Using Buggy and Peters' [15] simplified approach, where a range of 3 to 12 months for time of preload removal, t_R, was applied and assessing time at initiation of creep, t_S, from Eq. (8), with *OCR* varying from 1.2 to 1.4, the estimated t_S values are from 6 months to 5.5 years. Using the C'_α values from Kalibaru in Figure 5, the creep strains, ε_c, shown in Figure 10 are much smaller than those from Mesri's observational method.

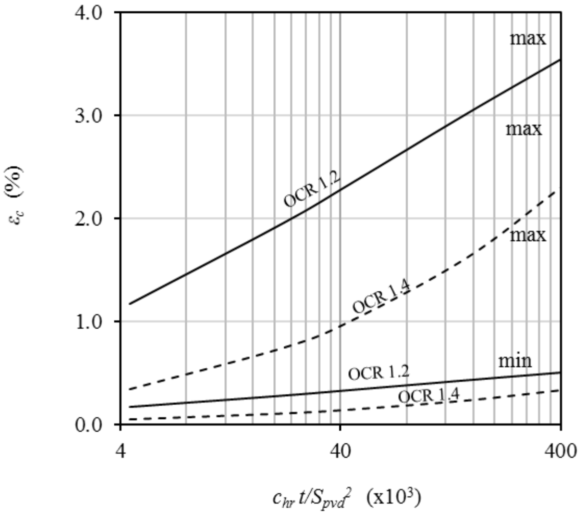

Figure 9 Creep strains, εc, from Mesri's [12] observational method.

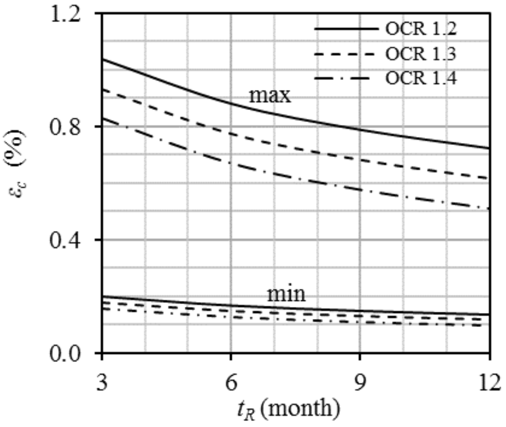

Figure 10 Creep strains, εc, from Buggy and Peters' [13] method.

The result of creep strain analysis described above shows that the difference in strain estimates are large and is heavily related to the different creep initiation time following preload removal. Buggy and Peters' [15] t_S values are siginificantly higher than t_l from Mesri's [12] laboratory based observational method. It is also clear that Buggy and Peters' [15] method ignores the effect of the PVD on the rebound rate during preload removal. On the other hand, it may be too risky to extend the laboratory test observations to large scale field conditions. The results also show, by both methods, even though 40% of the $(C_c - C_r)/C_a$ values are much higher than 25, ε_c could be as large as 1 to 3% for both, 85% by Mesri's [12] method, and 47% by Buggy and Peters' [15] method. This result will amount to a large creep deformation over the service lifetime for thick clay layers.

5 Conclusions

An experimental research was conducted in the interest of creep deformation analysis for reloading to high container yard design pressures beyond preload removal pressures. The loading in the research differed from earlier works with sustained loads: reloading above preload removal load but below pre-consolidation pressure was applied. Although the primary to secondary compression ratio, $(C_c - C_r)/C_\alpha$, falls into a negligible creep category in a typical *SSC* model in PLAXIS analysis, the estimated creep strains obtained in this research could amount to large creep deformations. Verification in future research on this issue is recommended.

A very high variation in creep index values was observed at *OCR* values less than 1.5. This means, since test results suggested that available predictive correlations are not always valid and since the data scatter is significant even at close agreement between regression and predictions, the estimation of creep in after preload removal at an OCR ~ 1 to 1.5 is challenging. Nevertheless, the results also demonstrated that surcharging the clay to OCR values as low as 1.2 will indeed result in a substantial reduction in creep deformation upon reloading.

The available methods to estimate creep deformation parameters can be applied easily, with minor adjustments in the formulations. However, the large difference in the analysis results requires more elaboration on the effect of PVD presence on the field on the estimation of time at creep initiation following the preload removal and reloading schedule.

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Nomenclature

C_c = compression index
C_r = recompression index
C_α = coefficient of secondary compression, or, creep index
$C_{\alpha\varepsilon(nc)}$ = creep strain rate for normally consolidated soil
$C_{\alpha\varepsilon(oc)}$ = creep strain rate for overconsolidated soil
C'_α = reloading creep index
C''_α = secant creep index during reloading after preload removal
c_{hr} = rebound coefficient of consolidation
e_o = initial void ratio
G_s = specific gravity
LL = liquid limit
L_o = thickness of soil sublayer
m = empirical constant, equals to C_r/C_c
N_{SPT} = standard penetration test blow counts
n = empirical constant
OCR = overconsolidation ratio
PI = plasticity index
PVD = prefabricated vertical drain
S = magnitude of creep settlement
S_{PVD} = PVD spacing in triangular configuration
SSC = Soft Soil Creep model in PLAXIS computation

t = time from initiation of creep settlement
t_l = time to end of secondary rebound
t_p = time to end of primary consolidation
t_{pr} = time to end of primary rebound
t_R = time at preload removal
t_S = time at start of creep after preload removal
w_n = natural water content
β = constant in Equation (6)
ε_c = creep strain
σ'_p = pre-consolidation pressure
σ'_v = vertical effective pressure

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