Evaluation of recompression index for structured clays from laboratory constant rate of strain consolidation tests

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ABSTRACT: There are well-established procedures available for performing consolidation tests and obtaining preconsolidation stress (σ'_p) and compression index ($C_{c\varepsilon}$) from these tests as well as adjusting measured values for the effects of sample disturbance. However, determination of the recompression index ($C_{r\varepsilon}$) has not gained nearly similar attention and no clear consensus has been provided in the literature on the best approach to perform consolidation tests and how to determine $C_{r\varepsilon}$ from the measured data. A suite of CRS tests on a variety of high-quality to highly disturbed samples of natural structured clays with unload-reload (U-R) cycles at different stress and strain levels were conducted to investigate the effects of stress level and unloading ratio on estimates of $C_{r\varepsilon}$. Different methods were used to estimate $C_{r\varepsilon}$ from the results of each U-R cycle. The results show a consistent increase in $C_{r\varepsilon}$ from almost all the methods with increasing stress level and unloading ratio. Different methods resulted in significantly different $C_{r\varepsilon}$ values specifically for higher OCR soils as well as sensitive clays. Based on the findings from this study recommendations for practice are provided for conduct of CRS tests and how to interpret the test results to best estimate $C_{r\varepsilon}$.

Keywords: recompression index; consolidation; CRS; clays

1. Introduction

The key soil properties for estimating primary consolidation settlement of fine-grained soils are the recompression index ($C_{r\varepsilon}$), preconsolidation stress (σ'_p), and compression index ($C_{c\varepsilon}$). They can readily be estimated from 1-D incremental loading (IL) or constant rate of strain (CRS) consolidation tests performed on good quality samples. The recompression index is the slope of the 1-D strain versus log effective stress curve (ε-logσ'_v) for recompression loading up to σ'_p while $C_{c\varepsilon}$ is the slope for virgin compression (i.e., normally consolidated) loading beyond σ'_p. The 1-D ε-logσ'_v compression curve can be adversely influenced by sample disturbance and hence estimating primary consolidation parameters can be unreliable in such cases.

Methods to determine $C_{c\varepsilon}$ and σ'_p, and the effect of sample disturbance on these parameters, have been extensively studied [1-6]. On the other hand, less research has been conducted on determination of $C_{r\varepsilon}$ and the effect of sample disturbance on this parameter. This is due to the much greater importance $C_{c\varepsilon}$ and σ'_p have on estimating the magnitude of settlement for soils loaded beyond σ'_p. However, $C_{r\varepsilon}$ can be a critical element in some cases such as for example heavy loads on thick layers of highly overconsolidated clay deposits and especially if the in situ soil remains in the recompression zone after loading. In such cases, difference in estimates of $C_{r\varepsilon}$ by a factor of 2 or 3 and beyond can have an important impact on the viability of a selected or desired foundation option. In addition, the Schmertmann method [1] of reconstructing the equivalent in situ compression curve from a laboratory curve measured on disturbed samples relies on accurate determination of $C_{r\varepsilon}$.

$C_{r\varepsilon}$ is strongly dependent on sample quality and increasing disturbance results in an increase in its laboratory measured value. Empirically $C_{r\varepsilon}$ can be estimated as a function of $C_{c\varepsilon}$, but the typical range of reported $C_{r\varepsilon}/C_{c\varepsilon}$ values spans an order of magnitude from 0.02 to 0.20 [7]. Determining $C_{r\varepsilon}$ from IL or CRS consolidation tests can be uncertain, especially at low stresses and stiff soils, due to the small strains, possible seating and apparatus errors, possible swelling, recompression of gas bubbles, and sample disturbance [2, 8, 9]. Furthermore, a decision needs to be made at which stage of the test to evaluate $C_{r\varepsilon}$. Common practice is to perform an unload-reload (U-R) cycle with an unloading stress (σ'_u) and reloading stress (σ'_r). But there does not appear to be a clear consensus on how this should be performed. Should the U-R cycle be performed prior to σ'_p or after (Fig. 1)? If after σ'_p, at what σ'_u value or vertical strain (ε_v)? What σ'_r value or unloading ratio (σ'_u/σ'_r) should be used for the U-R cycle? Should it match the estimated in situ overconsolidation ratio (OCR) or should the unload portion go back to the in situ vertical effective stress (σ'_{v0}) regardless of the stress or strain level it started at?

The objective of the research presented in this paper was to study various methods of conducting CRS tests on samples of several natural clays for estimating $C_{r\varepsilon}$. The tests were intentionally performed on natural samples with sample qualities ranging from very poor to excellent. A majority of the clays tested are considered to be structured which herein is defined as clays with bonding among particles and that exhibit a distinct yield stress during 1-D vertical loading [10].

CRS tests were performed using several U-R cycles for each test with either constant unloading overconsolidation ratio $OCR_{u\text{-}r} = \sigma'_u/\sigma'_r$ or constant σ'_r and at various σ'_u values, both around σ'_p and beyond σ'_p. The collective data set was examined and various methods were compared to create a better understanding of potential best practice methods for conducting CRS tests and data interpretation for estimating $C_{r\varepsilon}$.

The terms recompression and compression index are often used for both strain-based or void ratio-based values (i.e., slope of the recompression and virgin compression portions of the ε-logσ'_v and e-logσ'_v curves, respectively). In this paper, the recompression and compression indices refer to the slopes calculated from the ε-logσ'_v curves and the subscript ε is used in the corresponding notation, i.e., $C_{r\varepsilon}$ and $C_{c\varepsilon}$.

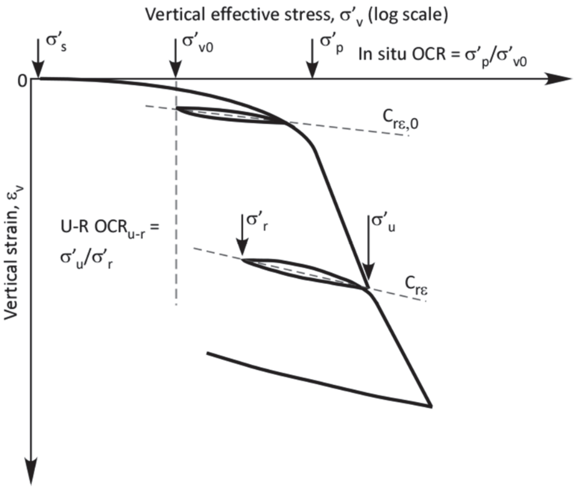

Figure 1. Two common procedures for estimating the recompression ratio, $C_{r\varepsilon}$ (after [3], [8] and [9]).

2. Background on Measurement of $C_{r\varepsilon}$

ASTM standard D2435/D2435M-11 for the 1-D IL test simply states "Specification of the stress level and the magnitude of an unload-reload cycle is the option of the agency requesting the test…" Leonards [8] recommended measuring $C_{r\varepsilon}$ from an U-R cycle with σ'_u at σ'_p (or $\sigma'_{v0}+\Delta\sigma'_v$ if $< \sigma'_p$ where $\Delta\sigma'_v$ is the design increase in vertical effective stress) and σ'_r at σ'_{v0} (Fig. 1). However, it is not clear how loading the specimen to σ'_p and unloading to σ'_{v0} would affect the recompression slope as the void ratio would be lower (much lower in case of highly disturbed samples) than the in-situ condition. In addition, conducting an U-R cycle around σ'_p could make estimating σ'_p more difficult using common graphic construction procedures, such as Casagrande's method, by possibly disrupting the continuous curvature of the compression curve around σ'_p.

ASTM D2435/D2435M-11 further states that for overconsolidated clays a better estimate of $C_{r\varepsilon}$ may be obtained by performing the U-R cycle after σ'_p is exceeded. Sandbaekken et al. [3] recommended determining $C_{r\varepsilon}$ from an U-R cycle starting from σ'_p or $2\sigma'_p$ and going back to σ'_{v0}. Lunne et al. [11] proposed the U-R cycle be performed at $2\sigma'_p$ or higher if needed to reach virgin compression and unloading to $OCR_{u\text{-}r} = \sigma'_u/\sigma'_r$ equal to the in-situ overconsolidation ratio ($OCR = \sigma'_p/\sigma'_{v0}$). DeJong et al. [12] performed CRS tests on resedimented intermediate soil samples with varying degrees of disturbance and recommended conducting the U-R cycle at $2.5\sigma'_p$ and unloading to the estimated K_0=1 condition. For these methods, with the U-R cycle performed at $\sigma'_u > \sigma'_p$, the void ratio at the start of the U-R is lower to much lower than the in situ void ratio.

Different values of σ'_u at which to perform the U-R cycle have been suggested. However, the slope of the U-R cycle tends to vary with σ'_u relative to σ'_p and the unloading $OCR_{u\text{-}r} = \sigma'_u/\sigma'_r$. Gunduz and Arman [13] investigated the effect of $OCR_{u\text{-}r}$ and initial void ratio (e_0) on $C_{r\varepsilon}$ for resedimented low-plasticity overconsolidated clayey samples. It was concluded that as e_0 increases $C_{r\varepsilon}$ increases and as laboratory unloading $OCR_{u\text{-}r}$ increases $C_{r\varepsilon}$ also increases.

With all these recommended methods there are practical considerations on when and how to perform the U-R cycle. Since σ'_p and sometimes σ'_{v0} are unknown before setting up a test it makes it difficult to specify a priori the conditions for conduct of the U-R cycle. Indeed it is typically the purpose of the test to estimate these very parameters. Unless the laboratory is required to keep close watch on the test and estimate σ'_p while the test is in progress. However, this may often not be practical and can be more costly, especially for larger commercial labs conducting many tests.

Another consideration for IL testing that is often left unstated in recommended methods for determining $C_{r\varepsilon}$ from IL tests is use of the end of primary compression curve rather than the end of increment compression curve. It generally makes little difference if the U-R cycle is performed at $\sigma'_v \leq \sigma'_p$ but can make an important difference if the U-R cycle is performed at $\sigma'_v > \sigma'_p$, especially for more structured soft clays with long load increments (e.g., traditional 24 hr increments).

If an U-R cycle is performed, several different methods have been presented in the literature to determine $C_{r\varepsilon}$ from the cycle which can result in different estimates. In some publications, it is not explicitly described how $C_{r\varepsilon}$ values were calculated, although the most common approach appears to be taking the average slope of the U-R hysteresis cycle by connecting σ'_r to the intersection of the unloading and rebound curves (Fig. 1) as suggested by Leonards [8] and defined in this paper as $C_{r\varepsilon 0}$. Another practice is to measure $C_{r\varepsilon}$ as the slope of the line connecting σ'_u to σ'_r [3]. DeJong et al. [12] suggested that $C_{r\varepsilon}$ is overestimated for intermediate soils such as silts if evaluated from the σ'_u to σ'_r slope and recommended the slope of σ'_r to the larger of σ'_u/OCR or $\sigma'_u/2$ as a more accurate measurement. Das [14] suggested $C_{r\varepsilon}$ should be determined as the slope of the unloading section of the U-R cycle.

Vipulanandan et al. [15] conducted IL tests on nine different soft clay samples from Houston, TX and investigated three different methods to determine $C_{r\varepsilon}$: Leonards [8], Das [14], and connecting σ'_{v0} to σ'_p on an

U-R cycle. Three U-R cycles were performed at different σ'_u for each test and up to 760% difference in $C_{r\varepsilon}$ values were reported for the different methods within a single U-R cycle. It was also reported that $C_{r\varepsilon}$ increases, significantly in case of high plasticity soils, with increasing σ'_u.

3. Materials and Methods

3.1. Test Soils

Table 1 lists the index properties and soil classification according to the United Soil Classification System (USCS, ASTM D2487 [16]) of the soils tested in this study. The samples were collected using fixed piston Shelby tube [17] and Sherbrooke block sampler [18, 19]. The database comprises 11 samples of low to high-plasticity soils, although the majority are low plasticity, with liquid limit values determined using the Casagrande cup (ASTM D4318 [15]). The Boston Blue Clay (BBC) Shelby tube samples were collected from Boston, MA and the BBC Sherbrooke Block samples were collected from Newbury, MA [20]; the Presumpscot clay from Falmouth, ME, the Onsøy sample from Onsøy, Norway [21]; the Connecticut Valley Varved Clay (CVVC) from Amherst, MA [22], and the Leda clay from Gloucester, Canada. All the soils are marine clays except for CVVC, which is a lacustrine clay.

3.2. Sample Preparation

Samples of two broadly defined quality levels were tested to study the effects of sample disturbance on $C_{r\varepsilon}$. They included intact or "undisturbed" (Sherbrooke block samples and fixed piston Shelby tube samples) of various sample quality and laboratory disturbed. These latter samples were intentionally disturbed in the laboratory following the general procedures described in DeJong et al. [12]. This consisted of taking a section of an intact sample, covering it in plastic wrap, freezing it for a minimum of 24 hrs, and thereafter allowing it to thaw for a minimum of 24 hrs in a humid room with a controlled temperature of 11°C and relative humidity of >85%. Cracks typically developed in the samples when following this process.

Table 1. Summary of the sampler type and index and classification properties of the soil samples.

Sample	Soil	Sampler Type	Depth (m)	Ave. *w* (%)	*LL* (%)	*PI* (%)	*LI* (-)	USCS
M-4	BBC-1	Shelby Tube	16.0	41	-	-	-	-
UP3	BBC-1	Shelby Tube	13.1	41	28	10	2.3	CL
N1SBS10	BBC-2	Sherbrooke Block	7.0	43	37	13	1.5	CL
N2SBS2	BBC-2	Sherbrooke Block	5.6	49	45	20	1.2	CL
N2SBS3	BBC-2	Sherbrooke Block	6.0	45	48	21	0.9	CL
ST2	Leda Clay-1	Shelby Tube	6.4	35	32	13	1.2	CL
ST3	Leda Clay-1	Shelby Tube	9.4	30	30	12	1.0	CL
G1SBS7	Leda Clay-2	Sherbrooke Block	3.7	94	56	27	2.4	CH
BB-6	Presumpscot Clay	Sherbrooke Block	4.0	43	48	23	0.8	CL
OSBS8	Onsøy Clay	Sherbrooke Block	19.6	61	55	26	1.2	CH
NGESSBS3	CVVC	Sherbrooke Block	3.63	40	47	19	0.6	ML/CL

Notes: Average water content (*w*) from CRS tests, *LL* = liquid limit, *PI* = plasticity index, *LI* = liquidity index, *CL* = low plasticity clay, *CH* = high plasticity clay, *ML* = low plasticity silt

3.3. Consolidation Tests

The constant rate of strain (CRS) consolidation tests were performed in general accordance with ASTM D4186 *Standard Test Method for One-Dimensional Consolidation Properties of Soils Using Controlled-Strain Loading* and Sandbeakken et al. [3]. The tests were conducted using a GeoTac personal computer based test control and data acquisition system, which includes a load frame, flow pump, CRS consolidometer cell and Sigma-1™ CRS control and data acquisition software. Specimens were hand trimmed using a soil lathe together with a sharp trimming ring and sharp trimming tools. The top and bottom surfaces of the specimens were trimmed flat with a wire saw and a long sharp edged knife with the final trimmed right cylinder dimensions equaling a diameter of 63.5 mm and a height of 19.0 mm. Specimens were placed in the CRS cell with moist top and bottom filter stones. Specimens were initially incrementally loaded up to $0.25\sigma'_{vo}$ to $0.50\sigma'_{vo}$ (or 10 kPa for highly disturbed samples) before back-pressure saturation to 400 kPa at constant height to ensure no swelling. Constant rate of strain loading was performed at a rate that resulted in a normalized base excess pore pressure ratio of less than 10% in the normally consolidated range; this rate was typically 1%/hr ($2.8\text{x}10^{-6}$ s^{-1}). This strain rate is approximately 10 times the equivalent end of primary rate, i.e., zero excess pore pressure during CRS loading [23]. In all the tests, specimens were allowed to creep for 300 min after every load or unload step to allow the base excess pore water pressure to dissipate before reversing the loading direction. All measurements during testing were made using load, displacement and pressure transducers. The measured data were processed using the methods of Wissa et al. [24] and also described in ASTM D4186 and Sandbeakken et al. [3]. All vertical strains were computed taking into account the apparatus compliance which was determined using a stainless steel disk.

Tests were conducted on each soil in the following general sequence, although not all of these tests were performed on each sample (Table 2):

1. Constant $\sigma'_r = \sigma'_{v0}$: The first test on each soil was conducted on an intact block or tube sample by consolidating the specimen to around 10% strain (i.e., into the normally consolidated stress range) before performing the first U-R cycle. The specimen was then unloaded to σ'_{v0} followed by reloading with two additional U-R cycles at strains of about 15% and 20% prior to unloading to σ'_{v0} for each cycle. The σ'_p value from this specimen was used to estimate the sample in situ OCR.
2. Constant $\mathrm{OCR}_{\mathrm{u\text{-}r}} = \sigma'_u/\sigma'_r$: The second test on each soil was also performed on an intact sample but now the first U-R cycle was performed at approximately $(0.8\text{-}1.0)\sigma'_p$ and unloaded back to $\mathrm{OCR}_{\mathrm{u\text{-}r}}$ equal to the estimated sample in situ OCR from Test 1 with this U-R slope defined as $C_{r\varepsilon 0}$. Three other U-R cycles at strains similar to the first test were conducted, each followed by an unloading step with $\mathrm{OCR}_{\mathrm{u\text{-}r}} = \mathrm{OCR}$ unless OCR < 2 for which an $\mathrm{OCR}_{\mathrm{u\text{-}r}} = 3\text{-}4$ was used.
3. The third test was conducted on the laboratory disturbed samples and with U-R cycles similar to the first test.

Pirouzi [25] provides additional details on the test samples, test program, results, and data interpretation.

4. Test Results

4.1. Compression Behavior

Tables 2 and 3 summarize the consolidation results from the CRS tests performed for this study. Preconsolidation stresses were estimated using Casagrande method [26] and sample quality was determined using NGI method of $\Delta e/e_0$ at σ'_{v0} [5] and SQD method of ε_v at σ'_{v0} [8]. Fig. 2 and Fig. 3 present an example set of results for Sherbrooke block sample N2SBS3, with a $\Delta e/e_0$ sample quality of very good to excellent, in ε-logσ'_v and e-logσ'_v spaces. The laboratory disturbed sample categorized as poor quality and acted similar to a remolded sample with σ'_p over 85% less than that of the intact specimens. Beyond σ'_p, the intact specimens showed the behavior of a structured clay with a distinct break in the compression curve just beyond σ'_p and a steep $C_{c\varepsilon}$ that progressively decreases with increasing stress. In void ratio space (Fig. 2), all of the test specimens indicate a convergence at higher stresses and by extrapolation all appear to merge at approximately $0.4e_0$ which is in accordance with the findings of Schmertmann [1].

The abovementioned general observations were consistently noted for all test sets. Disturbed samples had initial void ratios 0.8-0.9 times smaller than those of the undisturbed samples. In addition, compression curves for all soils except for the CVVC specimen tended to merge at around $0.4e_0$. Table 3 presents the maximum $C_{c\varepsilon}$ slope ($C_{c\varepsilon,\max}$) measured for the different tests. $C_{c\varepsilon,\max}$, as expected, is higher for undisturbed samples and decreases significantly for disturbed samples. $C_{c\varepsilon,\max}$ is also higher in case of the more structured sensitive soils as corroborated by the higher liquidity index (LI) values listed in Table 1 for those samples.

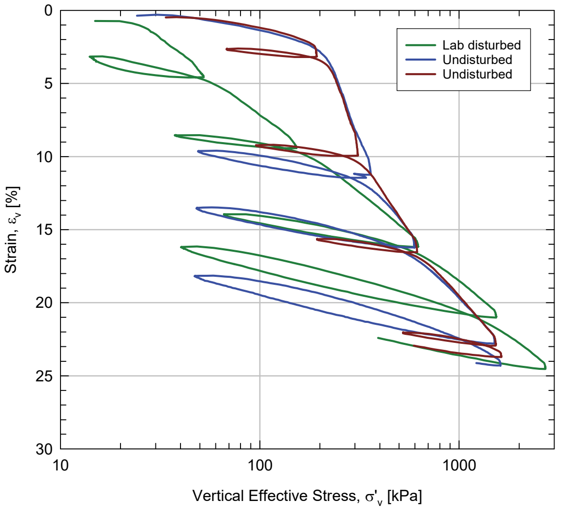

Figure 2. One-dimensional compression behavior of Sherbrooke block sample N2SBS3 in ε-logσ'_v space.

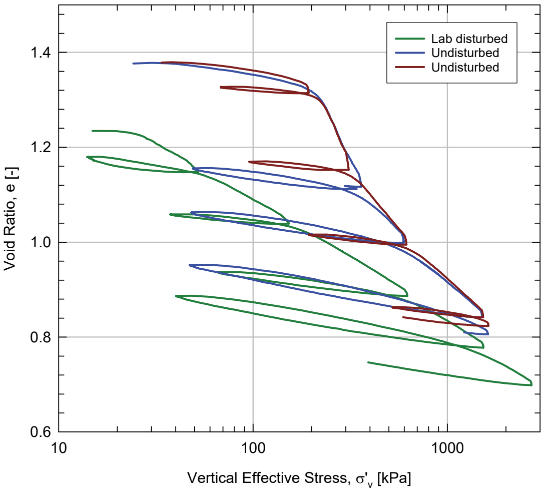

Figure 3. One-dimensional compression behavior of Sherbrooke block sample N2SBS3 in e-logσ'_v space.

4.2. Recompression Index – example data set

Two different definitions of $C_{r\varepsilon}$ were used in this study for interpretation of the U-R cycles (Fig. 4): 1) $C_{r\varepsilon 1}$ as the slope of the line from σ'_r to σ'_u [3] and 2) $C_{r\varepsilon 2}$ as the slope of the line connecting σ'_r to the intersection of the unload and reload curves [8]. For tests with an U-R performed at approximately $(0.8\text{-}1.0)\sigma'_p$, $C_{r\varepsilon}$ from the U-R slope is defined as $C_{r\varepsilon 0}$ and computed using the $C_{r\varepsilon 1}$ method. For the initial loading portion of the compression curves from σ'_{v0} to σ'_p a representative recompression index was taken as the slope of the line joining σ'_{v0} to the Casagrande estimate of σ'_p and is defined as $C_{r\varepsilon,Casa}$.

Figs 2 and 3 show that the general slope of the U-R cycle increases with an increase in both σ'_u and $\mathrm{OCR}_{\mathrm{u\text{-}r}}$. For the U-R cycle performed at around σ'_p, $C_{r\varepsilon 0} = 0.012$ in comparison to $C_{r\varepsilon,Casa} = 0.035$ (Table 4). For U-R cycles performed after σ'_p those with constant $\mathrm{OCR}_{\mathrm{u\text{-}r}}$, approximately equal to the estimated in situ OCR = 3.0 in this case, $C_{r\varepsilon 1}$ equaled 0.015, 0.018 and 0.019 as ε_v at the start of the U-R cycle increased from 9.9, to 16.6 to 22.9%. For U-R cycles with σ'_r equal to σ'_{v0}, $C_{r\varepsilon 1}$ equaled

0.022, 0.024, and 0.031 as ε_v at the start of the U-R cycles increased from 11.5, to 16.2 to 22.8%. The corresponding $OCR_{u\text{-}r}$ for this latter set of tests equaled 7.0, 12.4, and 32.0 compared to the estimated in situ OCR = 3.0.

For the laboratory disturbed specimen, an estimate of σ'_p results in a value significantly less than σ'_{v0}, additional confirmation of the high degree of disturbance induced in this specimen. As such, it was not possible to make an estimate of $C_{r\varepsilon,Casa}$. It is evident, however, that even the first U-R cycle with $C_{r\varepsilon 1} = 0.024$ (vs 0.012) was influenced by the sample disturbance. Whereas once the disturbed sample compression curve approached that of the high quality block sample tests, the U-R cycles conducted with $\sigma'_r \approx \sigma'_{v0}$, resulted in similar $C_{r\varepsilon 1}$ values of 0.023 (vs 0.024) and 0.030 (vs 0.031) for ε_v at start of U-R equal to 16.2 and 21.0%, respectively (Table 4).

Table 2. Summary of specimen properties, stress history, and sample quality – soil type in Table 1

Sample	Test No.	Condition†	w (%)	e_0 (-)	γ_t (kN/m^3)	σ'_{v0} (kPa)	σ'_p (kPa)	OCR *(-)*	At σ'_{v0}		Sample Quality	
									$\Delta e/e_0$ (-)	ε_v (%)	*NGI*	*SQD*
M-4	CRS273	U	41	1.08	17.8	182	280	1.54	0.047	2.5	2	C
UP3	CRS293	U	42	1.14	17.5	147	245	1.68	0.047	2.5	2	C
	CRS296	U	37	1.16	16.7	147	208	1.42	0.057	3.1	2	C
	CRS297	U	42	1.08	18.1	147	208	1.42	0.046	2.4	2	C
	CRS298	D	43	1.08	18.1	147	73	0.50	0.150	7.8	2	C
ST2	CRS278	U	36	1.00	18.2	82	159	1.96	0.029	1.5	1	B
	CRS279	U	34	0.98	18.4	82	182	2.23	0.020	0.97	1	A
ST3	CRS280	U	32	0.93	18.4	107	132	1.23	0.041	2.0	2	B
	CRS281	U	28	0.83	18.8	107	134	1.25	0.015	0.68	1	A
N1SBS10A	CRS274	U	41	1.22	16.8	81	190	2.35	0.022	1.2	1	B
	CRS309	U	41	1.29	16.9	81	210	2.59	0.013	0.72	1	A
	CRS317	D	46	1.21	17.5	81	21	0.26	0.162	8.7	4	E
N2SBS2	CRS288	U	53	1.44	16.6	67	244	3.65	0.023	1.3	1	B
	CRS289	U	53	1.44	16.6	67	244	3.65	0.026	1.5	1	B
	CRS303	D	49	1.41	16.4	67	71	1.07	0.092	5.4	3	D
N2SBS3	CRS282	U	50	1.39	16.6	70	212	3.03	0.016	0.92	1	A
	CRS283	U	52	1.39	16.8	70	212	3.03	0.013	0.76	1	A
	CRS304	D	47	1.25	17.2	70	42	0.60	0.101	5.6	3	D
BB-6	CRS310	U	50	1.41	16.4	46	152	3.35	0.006	0.34	1	A
	CRS312	U	49	1.40	16.4	46	152	3.35	0.004	0.24	1	A
	CRS314	D	44	1.20	17.3	46	49	1.08	0.066	3.6	3	C
OSBS8	CRS286	U	61	1.68	16.1	117	132	1.13	0.026	1.6	1	B
NGESSBS3	CRS290	U	43	1.19	17.3	43	315	7.33	0.009	0.47	1	A
	CRS295	U	37	0.99	18.3	43	326	7.59	0.004	0.22	1	A
	CRS305	D	39	1.10	17.6	43	131	3.06	0.046	2.4	2	C
G1SBS7	CRS276	U	91	2.70	14.3	33	81	2.45	0.007	0.55	1	A
	CRS277	U	96	2.84	14.1	33	81	2.45	0.007	0.55	1	A

Note: †U = undisturbed, D = laboratory disturbed,

Table 3. Summary of representative compression and recompression index values for various U-R cycles – soil type and properties in Tables 1 and 2

Sample	Test No.	Condition†	$C_{c\varepsilon,max}$	$C_{r\varepsilon,Casa}$	$C_{r\varepsilon 0}$ $\sigma'_u \approx \sigma'_p$	σ'_u (kPa)	$C_{r\varepsilon 1}$	σ'_u (kPa)	$C_{r\varepsilon 1}$	σ'_u (kPa)	$C_{r\varepsilon 1}$	σ'_u (kPa)	$C_{r\varepsilon 1}$
M-4	CRS273	U, $\sigma'_r \approx \sigma'_{v0}$	0.156	0.030		168	0.011	776	0.021	2383	0.019	-	-
UP3	CRS293	U, $\sigma'_r \approx \sigma'_{v0}$	0.186	0.022	0.008	736	0.023	-	-	-	-	-	-
	CRS296	U, $OCR_{u\text{-}r}$	0.195	0.014		191	0.008	422	0.014	747	0.018	1527	0.016
	CRS297	U, $\sigma'_r \approx \sigma'_{v0}$	0.185	0.021		227	0.016	424	0.018	748	0.022	1527	0.028
	CRS298	D, $\sigma'_r \approx \sigma'_{v0}$	0.127	-		187	0.013	439	0.017	760	0.022	1535	0.027
ST2	CRS278	U, $\sigma'_r \approx \sigma'_{v0}$	0.167	0.018	0.002	390	0.010	536	0.013	1455	0.019	-	-
	CRS279	U, $OCR_{u\text{-}r}$	0.168	0.024		230	0.002	864	0.003	1192	-	3229	0.008
ST3	CRS280	U, $\sigma'_r \approx \sigma'_{v0}$	0.130	0.032	0.002	204	0.002	391	0.010	508	0.009	1413	0.015
	CRS281	U, $OCR_{u\text{-}r}$	0.103	0.009		488	0.005	585	0.006	1763	0.007	-	-
N1SBS10A	CRS274	U, $\sigma'_r \approx \sigma'_{v0}$	0.180	0.047	0.010	169	0.021	775	0.024	2394	0.022	-	-
	CRS309	U, $OCR_{u\text{-}r}$	0.310	0.043		170	0.010	317	0.012	813	0.016	-	-
	CRS317	D, $\sigma'_r \approx \sigma'_{v0}$	0.101	-		122	0.009	323	0.012	953	0.020	-	-
N2SBS2	CRS288	U, $\sigma'_r \approx \sigma'_{v0}$	0.290	0.032	0.015	422	0.025	741	0.033	1489	0.036	-	-
	CRS289	U, $OCR_{u\text{-}r}$	0.280	0.032		229	0.015	426	0.020	753	0.021	1509	0.022
	CRS303	D, $\sigma'_r \approx \sigma'_{v0}$	0.126	-		63	0.018	24	0.017	746	0.026	1543	0.031
N2SBS3	CRS282	U, $\sigma'_r \approx \sigma'_{v0}$	0.340	0.035	0.012	352	0.022	617	0.024	1560	0.031	-	-
	CRS283	U, $OCR_{u\text{-}r}$	0.370	0.035		233	0.012	320	0.015	636	0.018	1579	0.019
	CRS304	D, $\sigma'_r \approx \sigma'_{v0}$	0.124	-		53	0.024	153	0.014	623	0.023	1535	0.030
BB-6	CRS310	U, $\sigma'_r \approx \sigma'_{v0}$	0.370	0.026	0.004	230	0.009	418	0.014	876	0.017	-	-
	CRS312	U, $OCR_{u\text{-}r}$	0.390	0.026		145	0.004	232	0.009	420	0.012	876	0.014
	CRS314	D, $\sigma'_r \approx \sigma'_{v0}$	0.113	-		180	0.007	390	0.014	724	0.017	1478	0.020
OSBS8	CRS286	U, $\sigma'_r \approx \sigma'_{v0}$	0.390	0.021	-	205	-	351	0.015	645	0.022	-	-
NGESSBS3	CRS290	U, $\sigma'_r \approx \sigma'_{v0}$	0.160	0.022	0.007	613	0.017	1321	0.024	2372	0.029	-	-
	CRS295	U, $OCR_{u\text{-}r}$	0.152	0.022		286	0.007	615	0.014	1318	0.022	2370	0.022
	CRS305	D, $\sigma'_r \approx \sigma'_{v0}$	0.134	-		114	0.011	231	0.012	768	0.020	1406	0.022
G1SBS7	CRS276	U, $\sigma'_r \approx \sigma'_{v0}$	1.14	0.027	0.007	53	0.007	92	-	117	0.018	-	-
	CRS277	U, $OCR_{u\text{-}r}$	2.26	0.027		85	0.011	91	0.012	122	0.013	-	-

Note: †U = undisturbed, D = laboratory disturbed, , U-R cycles performed either at constant $\sigma'_r \approx \sigma'_{v0}$ or constant $OCR_{u\text{-}r} \approx$ in situ OCR

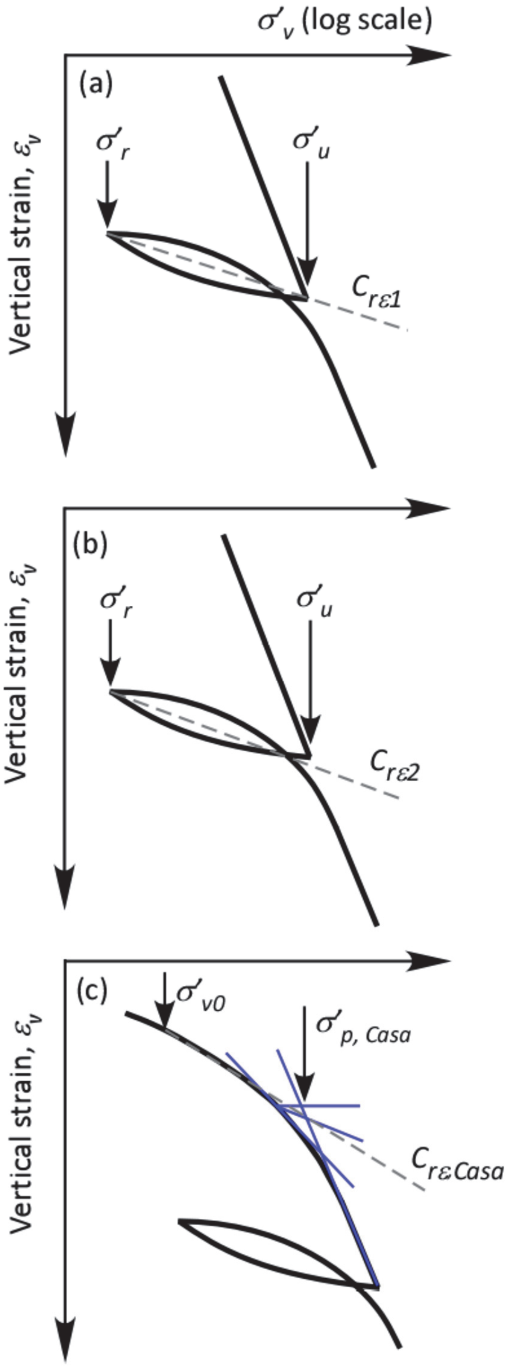

Figure 4. Different methods used to determine $C_{r\varepsilon}$ in this study.

Given the very good to excellent quality of the undisturbed sample, it is reasonable to assume in this case that the $C_{r\varepsilon0}$ value of 0.012 for U-R with $\sigma'_u \approx \sigma'_p$ and $\sigma'_r \approx \sigma'_{v0}$ is most representative of the likely in situ value. Particularly for this higher LI soil for which possible particle bonding that was destructured by loading beyond σ'_p would allow for greater swelling upon unload and thus greater recompression during reload. As it is, all other $C_{r\varepsilon1}$ values are greater than this value of 0.012 with the range from 0.015 to 0.031 (Table 4) with the largest values being for greater values of ε_v, σ'_u and $OCR_{u\text{-}r}$.

Table 4. Summary of recompression index values for Boston Blue Clay Sherbrooke block sample N2SBS3

Test	U-R #	σ'_u kPa	σ'_u/σ'_p	ε_v (%)	σ'_r kPa	$OCR_{u\text{-}r}$	$C_{r\varepsilon1}$
CRS283	1	233	1.1	3.2	79	3.0	0.012
Undisturbed	2	320	1.5	9.9	99	3.2	0.015
	3	636	3.0	16.6	200	3.2	0.018
	4	1579	7.5	22.9	541	2.9	0.019
CRS282	1	352	1.7	11.5	51	7.0	0.022
Undisturbed	2	617	2.9	16.2	50	12.4	0.024
	3	1560	7.4	22.8	49	32.0	0.031
CRS304	1	53	0.3	4.6	14	3.7	0.024
Lab	2	153	0.7	9.4	35	4.3	0.014
Disturbed	3	623	2.9	16.2	66	9.4	0.023
	4	1535	7.2	21.0	40	38.0	0.030

Note: σ'_p = 212 kPa, σ'_{v0} = 70 kPa, OCR = 3.0, $C_{r\varepsilon,Casa}$ = 0.035, $C_{r\varepsilon0}$ = 0.012

4.3. Recompression Index – full data set

Tables 2 and 3 present representative results for the full data set. The recompression values presented in Table 3 are those for $C_{r\varepsilon1}$, i.e., slope of the line connecting σ'_r to σ'_u (Figure 4). As expected, there is little difference between the values of $C_{r\varepsilon1}$ and $C_{r\varepsilon2}$ with $C_{r\varepsilon1}$ values being on average about 8% larger as shown in Fig. 5.

Figs 6 and 7 plot $C_{r\varepsilon1}$ data from various U-R cycles for all soils tested with approximately constant unloading $OCR_{u\text{-}r}$ equal to the in situ OCR. Whether the data is plotted versus the strain at which the U-R cycle started (Fig. 6) or the corresponding stress ratio σ'_u/σ'_p (Fig.7) the data show a slight upward trend. This is markedly different than the results for tests performed with U-R cycles with constant σ'_r approximately equal to σ'_{v0}. Fig. 8 to 10 plot the $C_{r\varepsilon1}$ data for these tests versus the strain at which the U-R cycle started (Fig. 8), the corresponding stress ratio σ'_u/σ'_p (Fig. 9), and the unloading $OCR_{u\text{-}r}$ equal to σ'_u/σ'_r (Fig. 10). While there is scatter in the data set, there is a trend of increasing $C_{r\varepsilon1}$ with an increase in the size of the U-R cycle especially for individual soils.

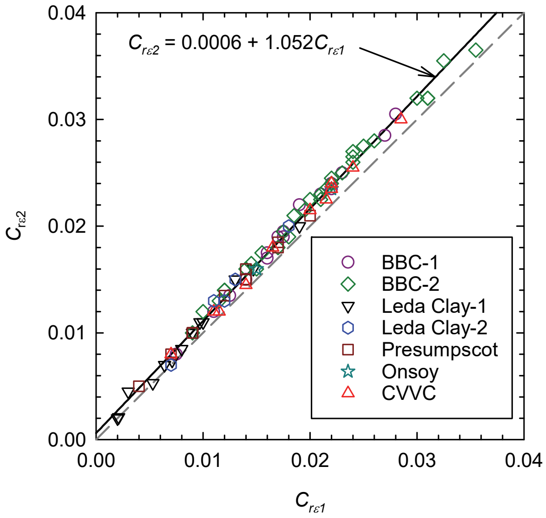

Figure 5. Relationship between $C_{r\varepsilon2}$ and $C_{r\varepsilon1}$ methods of evaluating the $C_{r\varepsilon}$ from an U-R cycle ($C_{r\varepsilon1}$ data presented in Table 3).

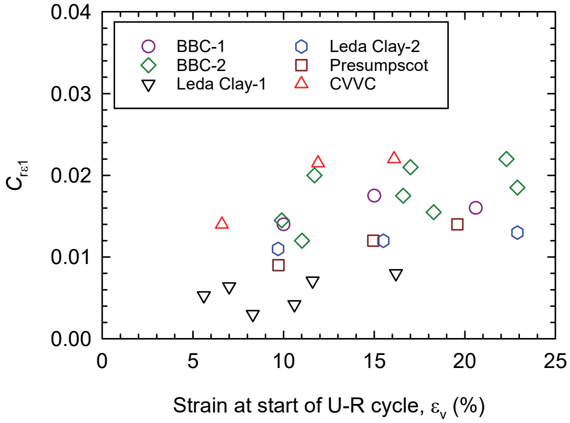

Figure 6. $C_{r\varepsilon 1}$ versus strain at start of the U-R cycle for tests performed with constant OCR$_{\text{u-r}}$ equal estimated in situ OCR.

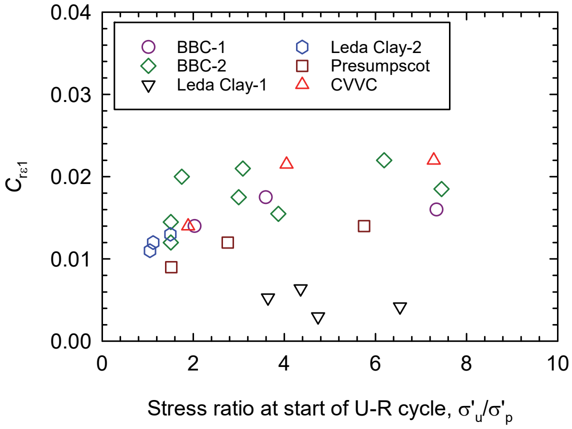

Figure 7. $C_{r\varepsilon 1}$ versus stress ratio σ'_u/σ'_p at start of the U-R cycle for tests performed with constant OCR$_{\text{u-r}}$ equal to the in situ OCR.

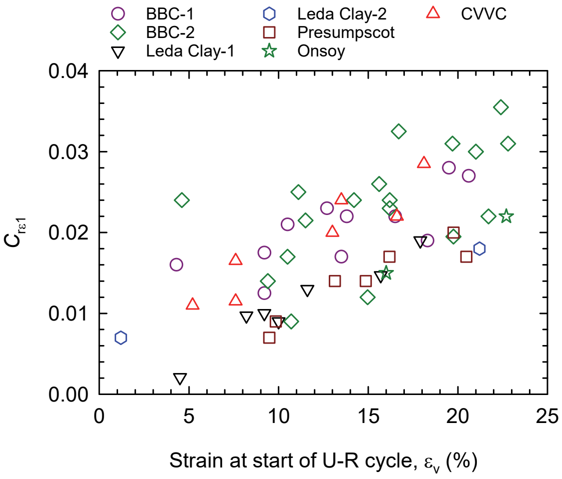

Figure 8. $C_{r\varepsilon 1}$ versus strain at start of the U-R cycle for tests performed with constant σ'_r equal σ'_{v0}.

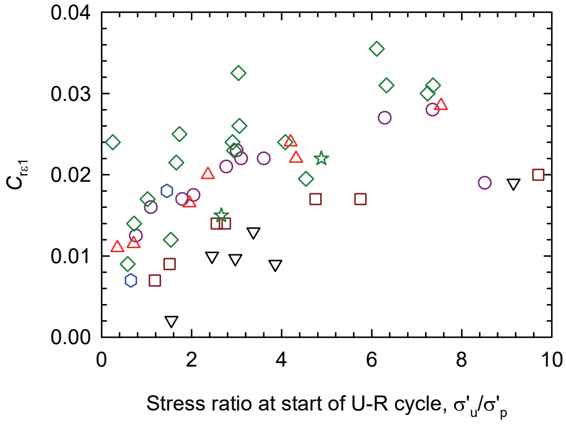

Figure 9. $C_{r\varepsilon 1}$ versus stress ratio σ'_u/σ'_p at start of the U-R cycle for tests performed with constant σ'_r equal σ'_{v0}.

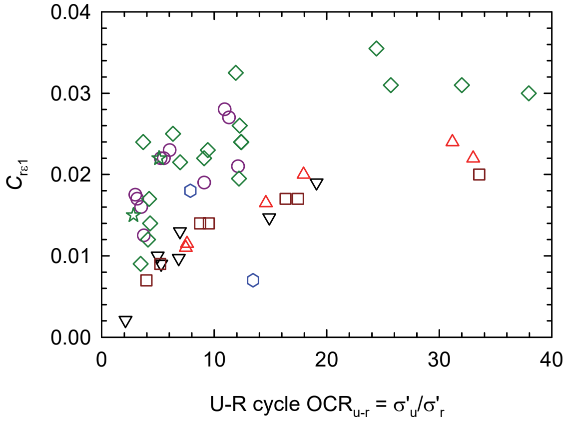

Figure 10. $C_{r\varepsilon 1}$ versus U-R cycle unloading OCR$_{\text{u-r}}$ for tests performed with constant σ'_r equal σ'_{v0}.

Figures 11 and 12 plot data for the undisturbed samples of the ratio of $C_{r\varepsilon 1}$ for U-R cycles to that of $C_{r\varepsilon 0}$ measured with the U-R cycle performed at $\sigma'_u \approx \sigma'_p$. The ratios are plotted versus the strain at the start of the U-R cycle for tests conducted with constant OCR$_{\text{u-r}}$ equal to the in situ OCR (Fig. 11) and with constant σ'_r approximately equal to σ'_{v0} (Fig. 12). In all cases $C_{r\varepsilon 1}$ values are greater than that measured with the U-R performed at $\sigma'_u \approx \sigma'_p$ and with much greater ratios for tests with an increase in the value of OCR$_{\text{u-r}}$.

Values of $C_{r\varepsilon,Casa}$ were also greater than that of $C_{r\varepsilon 1}$ for U-R with $\sigma'_u \approx \sigma'_p$ by a factor ranging from 2 to 6 for the majority of the test soils. Overall $C_{r\varepsilon,Casa}$ had the highest average and range of results which suggests it is most influenced by sample disturbance.

For the laboratory disturbed samples, once the compression state reached a strain of greater than apporximately 10%, the $C_{r\varepsilon 1}$ values were similar to that of the intact undisturbed samples.

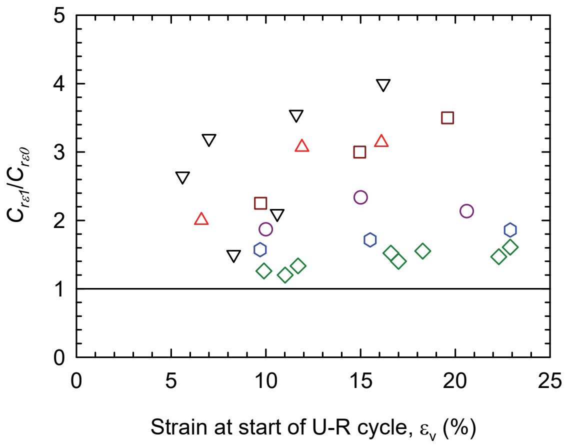

Figure 11. Ratio of $C_{r\varepsilon1}$ to $C_{r\varepsilon0}$ versus strain at start of U-R cycle for tests performed with constant $\mathrm{OCR}_{\text{u-r}}$ equal in situ OCR.

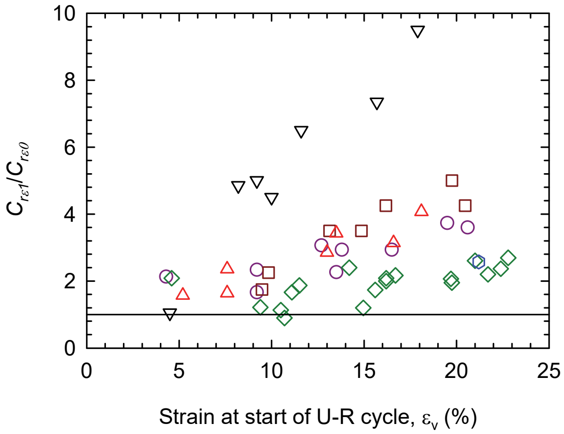

Figure 12. Ratio of $C_{r\varepsilon1}$ to $C_{r\varepsilon0}$ versus strain at start of U-R cycle for tests performed with constant σ'_r equal σ'_{v0}.

5. *Discussion of Results*

The results presented in the previous section show that $C_{r\varepsilon1}$ can vary significantly depending on the method used to measure it. In all cases, the values of $C_{r\varepsilon,Casa}$ and $C_{r\varepsilon1}$ for various U-R cycles conducted at unloading stresses σ'_u greater than σ'_p is greater than $C_{r\varepsilon0}$ for $\sigma'_u \approx \sigma'_p$ and $\mathrm{OCR}_{\text{u-r}} \approx$ OCR.

Considering only U-R cycles conducted with unloading stresses σ'_u greater than σ'_p, $C_{r\varepsilon1}$ can still vary by a factor of around 1.5 to 3 for an individual specimen with the higher end of the range being for tests conducted with constant $\sigma'_r = \sigma'_{v0}$ cycles and for the largest $\mathrm{OCR}_{\text{u-r}}$ values. The data also confirm that values of $\mathrm{OCR}_{\text{u-r}}$ greater to much greater than the in situ OCR results in the largest values of $C_{r\varepsilon1}$ from U-R cycles conducted with $\sigma'_u > \sigma'_p$. These findings are generally independent of sample quality.

For an ideal sample with no disturbance, $C_{r\varepsilon,Casa}$ should most closely reflect the in-situ value. However, due to the unavoidable, and potentially variable, sample disturbance, $C_{r\varepsilon,Casa}$ will often overestimate the in situ $C_{r\varepsilon}$ value, sometimes by a significant amount. Thus conduct of the U-R cycle at $\sigma'_u \approx \sigma'_p$ and with $\mathrm{OCR}_{\text{u-r}} \approx$ OCR is considered to produce the most representative value of the in situ $C_{r\varepsilon}$. However, it is often not practical to conduct a test in this manner because the value of σ'_p is typically unknown beforehand. Furthermore, for poor quality samples the test will yield a low to much lower than realistic value of σ'_p. But once again, the sample quality is typically unknown until the test is performed when using the $\Delta e/e_0$ or SQD volumetric measures of sample quality.

The results also show that if an U-R cycle is to be performed at $\sigma'_u > \sigma'_p$ it should be performed relatively close to σ'_p. But not too close such that it possibly disrupts the compression curve around σ'_p making it more difficult to interpret using common graphical procedures. The data presented in Table 2 and 3 indicate that $C_{r\varepsilon1}$ value measured for the first U-R beyond σ'_p typically results in a value of $C_{r\varepsilon1}$ that ranges from 1.4 to 2.5, with an average value of 2.0, greater than $C_{r\varepsilon0}$ measured for the U-R cycle at $\sigma'_u \approx \sigma'_p$ and $\mathrm{OCR}_{\text{u-r}} \approx$ OCR.

While the $C_{r\varepsilon2}$ method of interpreting U-R cycle data appears to be popular in practice, the $C_{r\varepsilon1}$ method has the advantage that it can be applied to any U-R loop. That is, once test results have been obtained and it is decided the U-R cycle $\mathrm{OCR}_{\text{u-r}}$ was too large the $C_{r\varepsilon1}$ method can nevertheless be applied to that cycle using any selected value of σ'_r along the unloading portion of the cycle and simply connecting it back to the cycle σ'_u value.

6. *Recommendations*

The best case scenario in practice is to have high quality samples and to perform an U-R cycle equal to or close to σ'_p and use an $\mathrm{OCR}_{\text{u-r}} \approx$ OCR. In the case of lower quality samples it is better to perform the U-R cycle at around $\sigma'_u \approx 2\sigma'_p$ and use $\sigma'_r \approx \sigma'_{v0}$. This is the procedure recommended by Sandbaekken et al. [3]. However, as noted in the previous section, sample quality and σ'_p is typically unknown at the start of a test. Furthermore, the reliably of a σ'_p estimate decreases with decreasing sample quality. This presents a practical challenge since it is more convenient for a laboratory to specify the test parameters at the beginning of a test. This is especially the case for computer controlled test equipment with automated application of the specified stress or strain conditions. Thus a pragmatic recommendation is to specify that the U-R cycle be conducted at around 10% strain and use $\sigma'_r \approx \sigma'_{v0}$. These test parameters can be readily specified before the start of a test using automated equipment and without a priori knowledge of sample quality and σ'_p. The resulting U-R cycle can be interpreted using $C_{r\varepsilon1}$ from any selected $\sigma'_r > \sigma'_{v0}$ along the unloading portion of the cycle or $C_{r\varepsilon2}$. The one caveat is that stiff to very stiff clays may not reach 10% axial strain during a standard consolidation test. Therefore a specified stress limit for commencement of the U-R cycle should also be included in the test loading schedule together with the 10% vertical strain criterion and conduct the U-R cyclic at whichever one triggers first.

7. *Conclusions*

There appears to be no consensus in the literature on best practice methods for conduct of 1-D consolidation tests for determining the recompression index of soils.

CRS test results from a variety of different quality samples prepared from block and Shelby tube samples were investigated in this study. Each test was performed with several U-R cycles at different stress levels and with different $\text{OCR}_{\text{u-r}} = \sigma'_u/\sigma'_r$ ratios to examine the effect on estimation of $C_{r\varepsilon}$. The results show that $C_{r\varepsilon 1}$ increases with increasing σ'_u/σ'_p, σ'_u/σ'_r, or ε_v at σ'_u.

The most representative value of $C_{r\varepsilon}$ is considered to be for conduct of an U-R cycle with $\sigma'_u \approx \sigma'_p$ and with $\text{OCR}_{\text{u-r}} \approx$ the estimated in situ OCR. However, this requires a high quality sample and a priori knowledge of sample quality and σ'_p. Thus in the absence of such knowledge before a test is conducted, a pragmatic recommendation is to specify that the U-R cycle be conducted at around 10% vertical strain and use $\sigma'_r \approx \sigma'_{v0}$. The primary advantage of this recommendation is that these test conditions can be specified before a test specimen is setup. The resulting U-R cycle can be interpreted using $C_{r\varepsilon 1}$ from any selected $\sigma'_r > \sigma'_{v0}$ along the unloading portion of the cycle or $C_{r\varepsilon 2}$. Conducting the U-R cycle at larger to much larger strain values is not recommended as this will result in larger $C_{r\varepsilon}$ values. A specified stress limit, especially for stiff to very stiff clays, for commencement of the U-R cycle should also be included in the test loading schedule together with the 10% vertical strain and the U-R cyclic should be conducted at whichever one triggers first.

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