Effect of Strain Rate and Creep on Clay Consolidation Behavior

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ABSTRACT: Results from a laboratory investigation program to investigate the consolidation strain rate and creep effects of San Francisco Old Bay Clay are presented. A total of 10 oedometer consolidation tests were performed, with five tests using incremental load (ICL) consolidation and five tests using constant rate of strain (CRS) consolidation. For ICL tests, the effect of incremental load duration on consolidation behavior was evaluated for approximately 1.0, 2.0, and 2.5 log cycles of time after the end of primary consolidation. For CRS tests, the effect of strain rate on consolidation behavior was evaluated for consolidation strain rates of 1.0%/hr, 0.1%/hr and 0.012%/hr during select normally consolidated strain intervals. A creep factor is proposed to quantify the reduction in compression stresses with increased load duration or decreased strain rate, and is used to represent the horizontal shift in the normal compression line due to simultaneous secondary compression.

Keywords: Consolidation, Strain Rate, Creep Behavior

1. Introduction

This paper presents the results and analysis of a laboratory investigation program to investigate the consolidation strain rate and creep effects for the Pleistocene age high-plasticity clay known locally as Old Bay Clay; a soil strata that underlies much of the San Francisco bay area in California, USA. A total of 10 oedometer consolidation were performed, with five tests performed using incremental load (ICL) and an additional five tests performed using constant rate of strain (CRS) consolidation.

The series of oedometer tests were performed on similar samples of Old Bay Clay to evaluate the effects of load duration and strain rate on the measured compression behavior. Five incremental consolidation load tests were performed with select load increment durations of 24, 240 and 720 hours, and five constant rate of strain tests were performed with strain rates of 1.0, 0.1, and 0.012 %/hr. Individual tests are presented first, followed by discussion of observations for individual tests, and then comparisons are made between tests with results indicating shifts in the compression behavior with increased load duration or decreased strain rate. A creep factor is defined for both ICL and CRS tests to quantify the reduction in effective stress with increased load duration or decreased strain rate.

2. Testing Methods

A series of oedometer tests were performed on tube samples obtained from the Old Bay Clay stratum that underlies much of San Francisco, CA. This section provides an overview of sample selection, specimen preparation, and ICL or CRS consolidation testing.

2.1. Sample Selection and Preparation

Consolidation tests were performed on Shelby tube samples (76.2 mm OD, 71.1 mm ID) obtained from two separate borings at depths of 34.8 and 43.9 meters below ground surface using a Pitcher Barrel sampler. All specimens for the ICL test series were obtained from the same tube, and the specimens for the CRS tests were obtained from the second tube.

X-ray imaging of tube samples was performed to visually identify zones of “disturbed” soil to aid in selection of intact specimens of the Old Bay Clay from each tube sample.

Soil samples were prepared for consolidation testing using a cutting, trimming, and extrusion procedure presented in [1]. In this procedure, vertically oriented Shelby tubes were cut using a pipe cutter and a wire saw. A set of circular clamps were used to constrain the tube near the cut location. A pipe cutter affixed with a thin, sharp cutting wheel was used to cut the tube. After cutting through the steel, a wire saw was used to detach the soil from the tube wall. The cut tube edge was deburred and the specimen was extruded from the tube using a hydraulic jack. After extrusion, the soil was trimmed using a trimming lathe and razor blades.

2.2. Incremental Consolidation Load Testing

Incremental consolidation load (ICL) tests were performed in accordance with ASTM D2435 [2] with exceptions as follows. The load duration of the first four initial recompression increments was less than 30 minutes. The specimen was inundated with water following the first full 24 hour load increment (typically increment 5). The load increment duration was varied for select increments to evaluate long term secondary compression effects. After application of 10 loading increments to a maximum stress of approximately 3.3 MPa, specimens were unloaded and oven dried to obtain the final moisture content and dry mass.

Time rate of consolidation was interpreted using the Casagrande approach [3] to determine the end of primary consolidation (EOP). Displacement readings for select long duration tests were used to report consolidation strains measured at the end of 24 hours (EO24), 240 hours (EO240), and 720 hours (EO720).

2.3. Constant Rate of Strain Consolidation

Constant rate of strain consolidation (CRS) tests were performed in accordance with ASTM D4186 [4] with exceptions as follows. Specimens were incrementally loaded to approximately 25% of the estimated in situ vertical effective stress (σ'_{v0}) prior to saturation and subjected to back pressure following the recommendations of [5]. Back pressure of 500 kPa was applied over a period of 6 hours using deaired, deionized water. Specimen height was fixed during back pressure and the specimen was typically left overnight prior to controlled rate of strain loading.

A reference strain rate of 1.0%/hr was sufficient to generate pore pressure ratios ($\Delta u/\sigma_v$) between 3-15% as required per ASTM D4186 [4] with typical $\Delta u/\sigma_v$ values of 6 to 9% when the specimen was in the normally consolidated region. Sufficient generation of pore pressure is necessary to reliably calculate the effective stress within the specimen and estimate the soil's consolidation coefficient. Tests were continued until either the device capacity of 2.8 MPa or until 25% total strain was reached. After completing the loading phase, specimens were unloaded at a rate of 0.5%/hr to a stress of 28.7 kPa, and held for 12 hours to allow for pressure equilibration within the specimen. The chamber was depressurized over a period of 2 hours, at which point the chamber was drained and the specimen unloaded. The specimen was then oven dried to obtain the final moisture content and dry mass.

Strain rate selection was bounded at the upper end by the reference strain rate and at the lower end by the displacement rate capabilities of the load frame actuator. For a nominal one inch thick specimen, the slowest achievable displacement rate corresponded to a strain rate of 0.012%/hr.

3. Test Results

3.1. Testing Sequence

The series of consolidation tests presented in this section were used to investigate the soil response to varying loading rates and creep durations. Results from a series of five incremental consolidation load tests are presented first (Table 1). The long-term creep deformation rate and the secondary compression strain index, $C_{\varepsilon\alpha}$ were examined by performing select ICL load increments for durations of 240 and 720 hours. This included two normally consolidated load increments for two separate tests held for a duration of 240 hours and two normally consolidated load increments for two additional tests held for a duration of 720 hours. Interpretation of time rate of consolidation from incremental loading was determined for EOP, EO24, EO240, and EO720 durations as appropriate for each test.

Table 1. Incremental load test matrix

Specimen # (-)	Specimen Depth (m)	Increments @ 24 hr (-)	Increments @ 240 hr (-)	Increments @ 720 hr (-)
ICL01	44.42	10	-	-
ICL02	44.36	8	2	-
ICL03	44.33	8	2	-
ICL04	44.15	8	-	2
ICL05	44.05	8	-	2

Five constant rate of strain consolidation tests were performed at varying strain rates of 1.0%/hr, 0.1%/hr, and 0.012%/hr (Table 2). The reference loading rate of 1.0%/hr was selected to achieve sufficient base pore pressure generation during normally consolidated loading. Reductions in strain rate occurred at targeted strain levels to evaluate the rate dependent compressibility of the soil. These reductions in strain rate were typically maintained for vertical strain increments of 3% to reduce the overall test duration and bound observations of strain rate reductions with the soil response at the reference rate measured above and below the 3% strain increment.

Table 2. Constant rate of strain test matrix

Specimen # (-)	Specimen Depth (m)	Stop Criteria (%)	Stop Criteria (MPa)	Strain Rate (%/hr)	Resulting Duration (days)
CRS07	35.27	25	2.78	1	2
CRS09.2	34.94	25	2.78	0.1,1	6
CRS10	34.85	25	2.78	0.1,1	6
CRS11	35.00	25	2.78	0.01,0.1,1	29
CRS12	34.85	25	2.78	0.01,1	16

3.2. Soil Classification

The soil obtained tube samples obtained at top of sample depths of 34.8 and 43.9 m was greenish gray clay and classified as Old Bay Clay with a plasticity range of 26 to 31 and a USCS classification of CH. Some small shell fragments were encountered during extrusion and trimming of the oedometer specimens. Results from companion classification tests and the index properties of the tested specimens are summarized in **Table** 3.

Table 3. Summary of soil properties

Specimen # (-)	Specimen Depth (m)	USCS[a] (-)	Moist Density Initial (g/cm³)	Moist Density Final (g/cm³)	Dry Density Initial (g/cm³)	Dry Density Final (g/cm³)	Moisture Content Initial (%)	Moisture Content Final (%)	Saturation % Initial (%)	Saturation % Final (%)	Void Ratio Initial (-)	Void Ratio Final (-)
ICL01	44.41	CH	1.91	2.05	1.36	1.58	39.7	29.3	93.7	92.7	1.186	0.884
ICL02	44.35	CH	1.88	2.05	1.33	1.56	41.5	31.8	92.3	95.6	1.248	0.920
ICL03	44.32	CH	1.79	2.03	1.28	1.54	40.2	32.2	84.3	95.8	1.336	0.941
ICL04	44.14	CH	1.87	2.04	1.33	1.55	41.0	31.3	91.8	95.1	1.250	0.923
ICL05	44.04	CH	1.95	2.08	1.40	1.60	39.6	29.6	98.2	96.4	1.130	0.860
CRS07	35.27	CH	1.90	2.07	1.35	1.56	41.5	32.5	95.3	100.0	1.218	0.911
CRS09.2	34.93	CH	1.90	2.04	1.32	1.52	43.8	34.1	97.7	99.2	1.250	0.960
CRS10	34.84	CH	1.91	2.04	1.33	1.52	44.0	34.6	98.7	100.1	1.248	0.966
CRS11	34.99	CH	1.95	2.07	1.40	1.59	39.0	30.6	96.5	97.6	1.131	0.878
CRS12	34.84	CH	1.93	2.09	1.38	1.60	39.7	30.2	96.0	98.3	1.157	0.859

Notes: [a]USCS - Unified Soil Classification System ASTM D2487; CH - fat clay. Plasticity range of 26 to 31. Classification data provided anonymously. Assumed specific gravity = 2.8

3.3. Incremental Consolidation Load (ICL)

A series of five incremental consolidation load tests (ICL) were performed (Table 1 and Table 3**Table**). Load durations of 24, 240, and 720 hours were chosen for normally consolidated increments and represent approximately 1.0, 2.0, and 2.5 log cycles of secondary compression, respectively. The subsections presented herein describe the stress-strain compressibility response for each test, time rate of consolidation for chosen normally consolidated increments, interpretation of the secondary compression strain index, and interpretation of incremental load creep factors.

3.3.1. Stress-Strain Response

The stress-strain response for test ICL05 summarized in Figure 1 is representative of tests ICL01 through ICL05. The stress-strain response for individual tests can be found in [6]. As an indicator of sample quality, the measured recompression strains required to reestablish in-situ overburden stresses were measured and resulted in SQD ratings of C [7], $\Delta e/e_0$ ratings of good to fair and poor [8], and C_r/C_c ratings of moderate [9]. For reference the [7-9] criteria are reported in Table 4. To overcome the effects of sample disturbance (likely due to sampler and

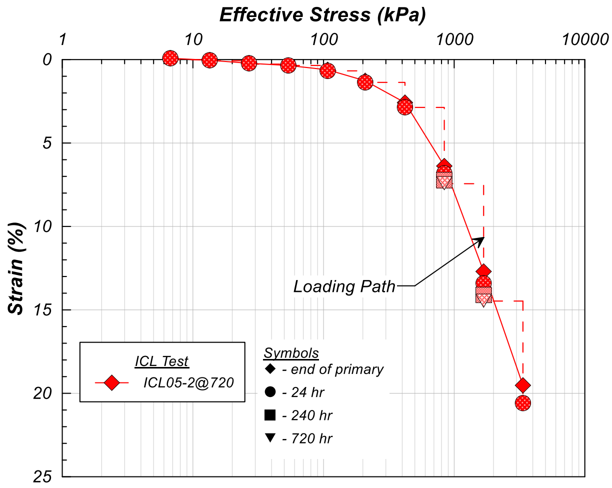

Figure 1. Stress-strain response for test ICL05 with end of primary consolidation determined using Casagrande interpretation.

sampling method, sample storage duration, and handling), the investigation of loading duration considered herein is performed on normally consolidated increments. Prior studies indicate the effects of sample disturbance can typically be overcome, or minimized, by loading to 1.5 to 2.0 times the soil's preconsolidation stress [10].

3.3.2. Time Rate of Consolidation

Proper interpretation of incremental load tests requires interpretation at the end of primary consolidation. Time rate of consolidation interpretation using Casagrande interpretation was performed for tests ICL01 through ICL05. The time rate of consolidation behavior for a select load duration of 720 hours is plotted in Figure 2.

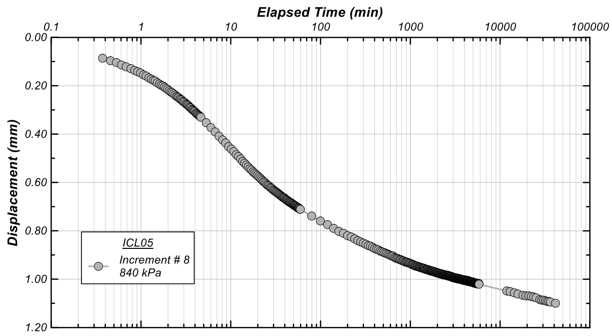

Figure 2. Time rate of consolidation for 720 hour loading increment from ICL05.

3.3.3. Secondary Compression

Secondary compression, defined as the additional strain that occurs after completion of primary consolidation, was interpreted from the log-linear slope of the void ratio (or strain) versus time plot (i.e., Figure 2). The log cycle of secondary compression was interpreted as the time past the end of primary consolidation (= $\log[t/t_{EOP}]$). From this time data, the secondary compression index ($C_\alpha = \Delta e$ per log-cycle of secondary compression time) and the secondary compression strain index ($C_{\alpha\varepsilon} = \Delta\varepsilon$ per log cycle of secondary compression time; $= C_\alpha/[1+e_0]$) were interpreted for all ICL tests at stresses from 418 kPa to 3340 kPa. For these samples, consolidation stresses of

Table 4. Sample quality assessment

Specimen	Specimen	Sample Quality								
#	Depth	$\varepsilon_{\sigma'v0}$	SQD^a	$e_{\sigma'v0}$	$\Delta e/e_0$	Rating[b]	C_r	C_c	C_r/C_c	Rating[c]
(-)	(m)	(%)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
ICL01	44.41	4.0	C	1.09	0.078	P.	0.12	0.51	0.24	Moderate
ICL02	44.35	3.2	C	1.15	0.079	P.	0.11	0.52	0.21	Moderate
ICL03	44.32	3.9	C	1.21	0.094	P.	0.15	0.46	0.33	Moderate
ICL04	44.14	3.2	C	1.16	0.072	P.	0.11	0.54	0.20	Moderate
ICL05	44.04	2.7	C	1.06	0.066	G.F.	0.09	0.48	0.19	Moderate
CRS07	35.27	1.9	B	1.18	0.031	V.G.E.	0.06	0.64	0.10	Excellent
CRS09.2	34.93	2.7	C	1.20	0.043	G.F.	0.12	0.57	0.20	Moderate
CRS10	34.84	2.3	C	1.20	0.040	V.G.E.	0.10	0.60	0.16	Moderate
CRS11	34.99	2.2	C	1.09	0.036	V.G.E.	0.07	0.48	0.14	Excellent
CRS12	34.84	2.7	C	1.10	0.049	G.F.	0.07	0.49	0.14	Excellent

Notes: [a]Terzaghi et al. (1996) Sample Quality Designation. [b]Lunne et al. (1997) quality rating: V.G.E=very good to excellent, G.F.=good to fair, P.=poor, V.P.=very poor. [c]DeJong et al. (2018) rating: Excellent=Cr/Cc <= 0.15, Moderate=0.15<Cr/Cc<0.4, Disturbed=Cr/Cc>0.4.

about 418 kPa (OCR=1.6 or 0.63σ′$_p$), 836 kPa (OCR=1.0 or 1.2σ′$_p$), 1700 kPa (OCR=1.0, 2.5σ′$_p$), and 3340 kPa (OCR=1.0, 5σ′$_p$) were used.

Figure 3 presents the measured secondary compression strains versus secondary compression time and Figure 4 presents the measured secondary compression strains for each consolidation stress and load duration. The average $C_{\alpha e}$ for a given stress level was determined by fitting a trendline from the origin through the data binned by stress level. The small secondary compression strains observed for the 416 kPa load increment occur due to overconsolidation. As consolidation stresses increase, the magnitude of secondary compression generally increases. The average $C_{\alpha\varepsilon}$ for a given stress level ranged from 0.0048, 0.0068, and 0.0059 for the normally consolidated increments at 836, 1700, and 3340 kPa, respectively. No distinguishable change in $C_{\alpha\varepsilon}$ was observed with increasing time for secondary compression.

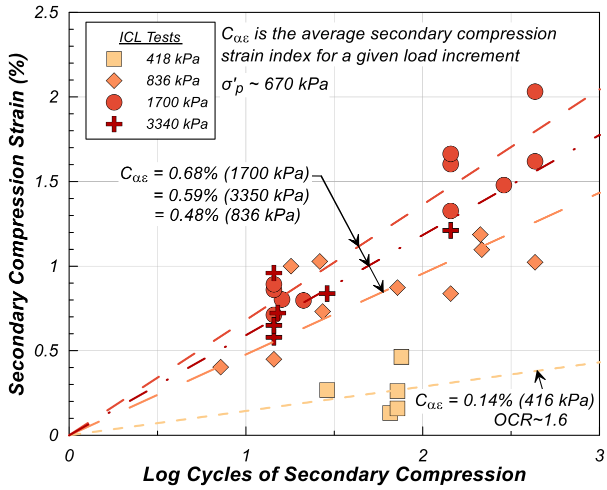

Figure 3. Summary of secondary compression strains (in percentage) for tests ICL01 through ICL05, including slightly overconsolidated (σ′$_v$=418 kPa) to normally consolidated load increments (σ′$_p$~670 kPa). Dashed lines are the best fit trendline through each stress increment and the slope represents the average secondary compression strain index for the given stress increment.

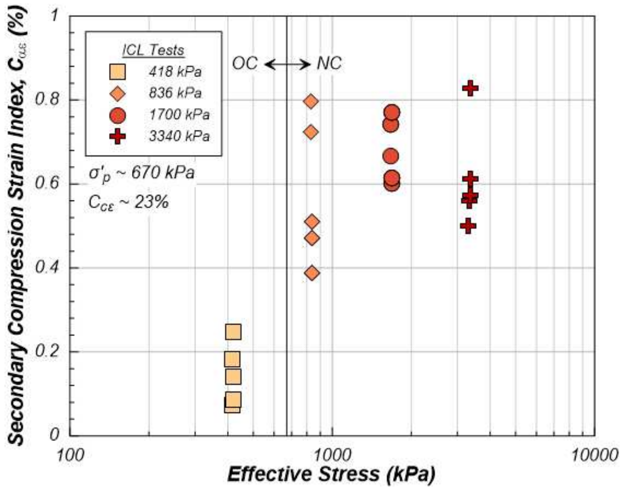

Figure 4. Summary of secondary compression strain indices (in percentage) from slightly overconsolidated (σ′$_v$=418 kPa) to normally consolidated (σ′$_v$>670 kPa) load increments for ICL01 through ICL05.

Figure 5 reports the four separate interpreted compression lines for end of primary, end of 24 hour, end of 240 hour, and end of 720 hour consolidation. The interpreted normal compression lines use the $C_{\alpha\varepsilon}$ for each test and load duration presented in Figure 3. These compression lines represent the vertical shift in the normal compression line that might be expected with increased load duration. Each compression line has the same slope ($C_{c\varepsilon}$) and is shifted vertically using the average $C_{\alpha\varepsilon}$ for the considered load duration.

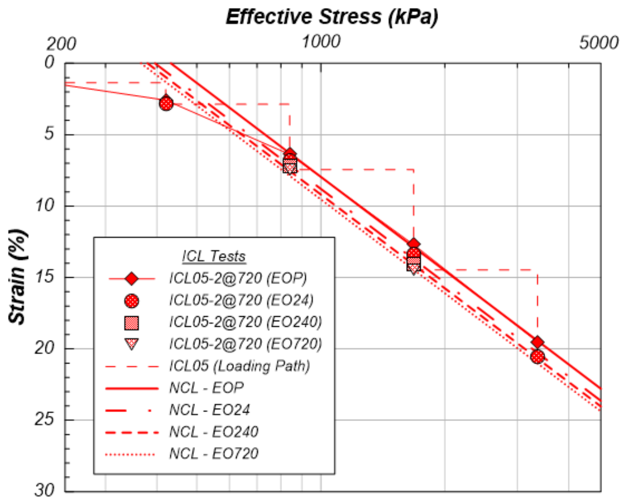

Figure 5. Compression plot for ICL05 indicating representative shifts in the normal compression line due to effects of secondary compression.

3.3.4. ICL Creep Factors

Following Mesri and Godlewski [11], a creep factor is defined herein to quantify the horizontal shift in the normal compression line due to secondary compression:

$$Creep\ Factor = \frac{\sigma'_{v,secondary}}{\sigma'_{v,NCL}} = 10^{-\frac{\Delta\varepsilon_{secondary}}{C_{c\varepsilon}}} \qquad (1)$$

where for a specific strain, σ'_v is the effective stress of the secondary compression line (SCL), $\sigma'_{v,NCL}$ is the corresponding effective stress of the normal compression line for end of primary loading, $\Delta\varepsilon_{secondary}$ is the amount of secondary compression strain for the given load duration, and $C_{c\varepsilon}$ is the compression ratio (i.e., slope of the normal compression line for end of primary loading). The range of creep factors determined for ICL01 through ICL05 are plotted against duration of secondary compression in Figure 6, indicating decreasing creep factor with increasing duration of secondary compression. The slope of the lines fit through data from each stress increment bin represents the decrease in creep factor per log-cycle of secondary compression. These creep factors for ICL tests indicate a decrease in measured EOP compression stresses of 4.0 to 6.0% per log cycle increase in secondary compression duration for normally consolidated conditions. As was observed with the secondary compression strains, the magnitude of the change in creep factor increases with increased increment stress, and then decreases slightly for the 3340 kPa load increment.

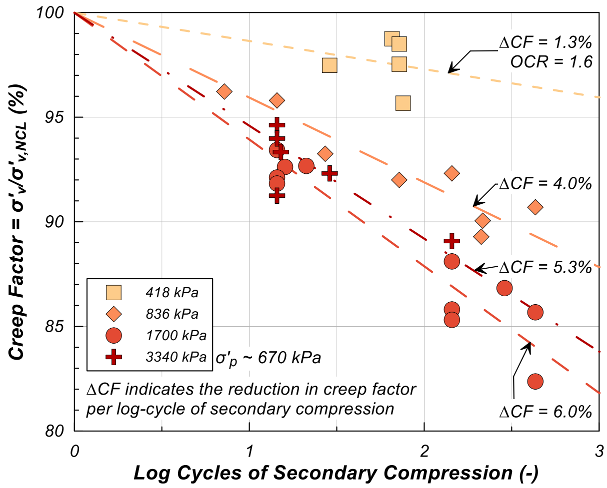

Figure 6. Summary of creep factors for various stress increments from ICL01 through ICL05. The dashed lines represent the best fit of the creep factors, with the slope of the line representing the magnitude decrease in creep factor per log cycle of secondary compression.

3.4. Constant Rate of Strain (CRS)

A series of constant rate of strain consolidation tests (CRS) were performed (Tables 2 and 3). A constant, reference strain rate of 1.0%/hour was used for test CRS07 to establish the representative end of primary compressibility of the soil. All tests started with a strain rate of 1.0%/hr, and then the strain rate was reduced for selected intervals of 3% strain or more. At the end of the reduced strain rate interval, loading was resumed at the reference rate of 1.0%/hr until completion, except for test CRS11. In this test, the strain rate was reduced from 1.0%/hr to 0.012%/hr for 3% strain, then increased to 0.1%/hr for an additional 3% strain, then increased to 1.0%/hr for 3% strain, and finally reduced to 0.012%/hr for the final 3% strain. CRS11 reached the load capacity of the test frame at the attempted final loading at 1.0%/hr, and as a result normal compression conditions were not obtained following the final strain rate reduction.

3.4.1. Stress-Strain Response

The measured stress-strain response to strain rate loading is shown for all CRS tests in Figure 7. Detailed stress-strain responses for individual tests can be found in [6]. Measured recompression strains to reestablish in-situ overburden stresses result in SQD ratings of C, $\Delta e/e_0$ ratings of good to fair and poor, and C_r/C_c of excellent to moderate with reference criteria reported in Table 4. These ratings are consistent with qualitative observations of sample quality during extrusion and trimming of the specimens as discussed previously.

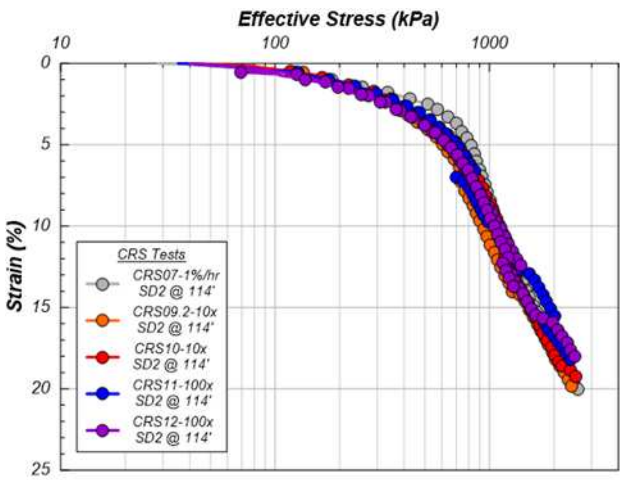

Figure 7. Compilation of CRS tests performed at variable strain rates.

The comparison of stress-strain behavior for an EOP interpreted ICL and CRS07 presented in Figure 8 demonstrates the agreement between the test methods for the Old Bay Clay. CRS testing provides higher resolution of the stress-strain behavior (data point for every 0.05% strain increment, rather than at specific stress intervals), which is particularly beneficial for observing transitions between recompression and normal compression that occur near the soil's preconsolidation stress [5].

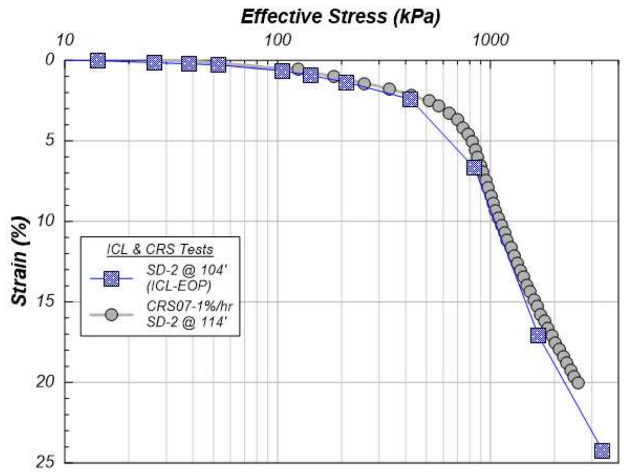

Figure 8. Comparison between CRS and ICL tests from boring SD-2.

Observations of stress-strain behavior for CRS tests with varying strain rate indicate a reduction in measured effective stress with reduced strain rate. The resulting shift in the stress-strain behavior is due to the increased contribution of secondary compression at low strain rates. The reduction in strain rate shifts the normal compression line, similar to observations from the ICL tests. Upon subsequent increase of the applied strain rate the stress-strain behavior shifts to the right (i.e., increased stiffness) and is consistent with the behavior prior to the strain rate reduction.

3.4.2. CRS Creep Factors

The role of strain rate on measured consolidation response is evaluated by estimating the normal compression line at the reference strain rate of 1.0%/hr. The reduction from a strain rate of 1.0%/hr to strain rates of 0.1%/hr and 0.012%/hr represent 1.0 and 1.92 log cycles of time for secondary compression to occur, respectively.

Figure 9 reports the creep factor, following [12], used to interpret normal compression behavior (i.e., end of primary consolidation) at the reference strain rate of 1.0%/hr for test CRS10. Consistent with the approach used to interpret the ICL data, the creep factor quantifies the horizontal shift in normal compression line due to the simultaneous occurrence of secondary compression, and is defined for CRS testing as:

$$Creep\ Factor = \frac{\sigma'_v}{\sigma'_{v,1\%/hr}} \qquad (2)$$

where for a specific strain, σ_v' is the effective stress measured at the reduced strain rate and $\sigma_{v,1\%/hr}'$ is the effective stress measured at the reference strain rate of 1.0%/hr. To obtain the creep factor for CRS tests, the compression curve for end of primary consolidation is interpreted for reduced strain rates and the creep factor is obtained using Eq. (2).

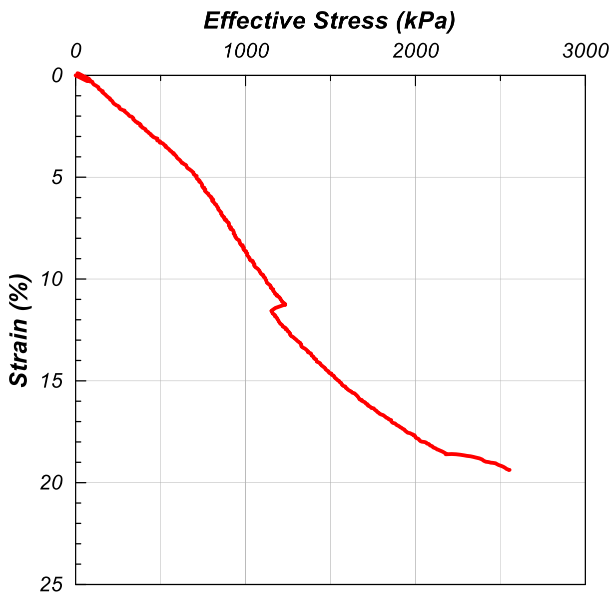

Figure 9. Compression curve for CRS10. Dashed line represents the interpreted end of primary compression curve scaled by the indicated creep factor (CF) using Eq (2).

The range of creep factors for CRS tests shown in Figure 10 are plotted against the log cycle decrease in strain rate and show a decreasing creep factor with decreasing strain rate. The slope of the line fit through the data points indicates a decrease in creep factor of 0.078 per log cycle increase in time for secondary compression for the CRS tests.