Constant rate of strain tests on reconstituted clay: a parametric study

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ABSTRACT

The paper presents and analyses results from nine constant rate of strain (CRS) consolidation tests on remolded kaolinite clay to study several practical aspects of constant rate of strain testing such as the effect of strain rates, back pressure, preconsolidation pressure and the quality of the consolidation parameters. The CRS results were compared to four incrementally loaded (IL) oedometer tests performed using standard procedures and one incremental loading test in the CRS cel with measurement of the permeability.

The results show that the CRS behavior of the reconstituted kaolinite clay is virtually independent of strain rate across the range tested. The consolidation parameters agreed well with the incremental loading test results, even at vertical effective stresses σ'_v close to or below the preconsolidation pressure σ'_p.

The widespread non-linear small strain theory (Wissa et al, 1971) is compared with the results obtained by a large strain theory (Lee, 1981), verifying that almost no differences exist. Lee's criterion for the evaluation of the applicability of a strain rate is found to be the best suited between several known criteria for the material tested.

The paper supports the validity of the large strain CRS theory and suggests that less structured clays such as those tested may have less rate dependence during consolidation than soils with strong interparticle bonding and structure.

INTRODUCTION

Consolidation tests are usually performed to determine stress-strain relationships in confined compression to obtain parameters for a reliable estimate of the magnitude and rate of settlement due to a stress increase caused by the construction of different structures.

For very long time the one-dimensional consolidation testing suggested by Terzaghi has been used. During the last three decades, however, various,continuous testing methods have been developed as an effort to gain resolution in defining the stress-strain curves for one-dimensional consolidation. Among them, the CRS test appears to be the most attractive. The method is standardized, requires only the use of a load frame (available in most laboratories) and has a well established theoretical basis. Furthermore, the CRS test has three distinct advantages over incremental loading:it provides continuous data for the stress-strain curve, the data can be processed without tedious and manual graphical analysis and the time to collect the data is remarkably reduced.

But at the same time, there are still several aspects that need further research which is probably the reason why its use is not widespread in current practice. Questions remain about allowable loading rates, rate dependence of consolidation properties and agreement between parameters obtained in IL versus CRS tests. This paper presents the results of a research program, in which an instrumented, computer-automated CRS consolidation cell was used together with standard IL tests to measure the consolidation behavior of a remolded kaolinite clay, in an attempt to clarify the influence of the strain rate on the quality of results in the loading and unloading behavior. These results are compared to data computed using CRS theories as well as to IL test results on the same soil and checked by permeability tests in the CRS cel, comparing the permeability calculated form the consolidation parameters with the measured one.
Furthermore, the accuracy in the calculation of the preconsolidation pressure and the validity of the consolidation parameters at lower stresses are studied in relation to the data of the standard IL test.

CRS CONSOLIDATION TEST

The one-dimensional CRS consolidation test is an efficient and relatively rapid method to determine consolidation properties, including stress history, compressibility, hydraulic conductivity, and time rate consolidation. It provides continuous data, permits easier conversion to automation and is faster than IL tests.
The procedure is standardized (i.e. ASTM-D-4186-89). The sample, drained at the top and undrained at the bottom, is loaded at constant rate without undue distress arising from continued high pore-pressure response. Deformations, applied force and excess pore water pressure are measured at adequate and frequent time intervals. The consolidation parameters may then be evaluated through any of the theories available.

Analysis methods for CRS tests

Several theories are available for the interpretation of CRS tests. The most common ones are the small strain solution (Wissa, Christian, Davis and Heiberg, 1971) and the large strain theory (Lee, 1981).

Appart from the general assumptions used in 1D consolidation, the non-linear, small strain theory assumes a constant coefficient of consolidation, C_v, and compression ratio, $C'_c = d\varepsilon / d(\log \sigma'_v)$

Based on these assumptions, equations were developed to calculate the average effective stress, $\sigma'_{v(ave)}$, the coefficient of consolidation C_v and the coefficient of volume change, m_v, provided no transient conditions exist:

$$\sigma'_{v(ave)} = \left(\sigma_v^3 - 2 \cdot \sigma_v^2 \cdot u_b + \sigma_v \cdot u_b^2\right)^{1/3} \quad (1)$$

$$C_v = -\frac{H^2 \cdot \log\left(\frac{\sigma_{v2}}{\sigma_{v1}}\right)}{2 \cdot \Delta t \cdot \log\left(1 - \frac{u_{b(ave)}}{\sigma_{v(ave)}}\right)} \quad (2)$$

$$m_v = \frac{\Delta H}{H} \cdot \frac{1}{\sigma'_{v(ave)} \cdot \ln(\sigma_{v2} / \sigma_{v1})} \quad (3)$$

where σ_v = total vertical stress, σ_{v1} and σ_{v2} = total vertical stresses at two times of difference Δt, H = current specimen height, $\sigma_{v(ave)}$ = average total vertical stress, u_b = pore water pressure at the base of the sample and ΔH = settlement of the sample within the time interval.

The small strain assumption however is not realistic in practice because strain magnitudes as high as 30% are encountered during CRS tests. Also the type of strain in most small strain theories is not well defined and can have ambiguous interpretations. Under these circumstances a finite strain theory is thought to be much appropiate.
In the large strain theory from Lee a normalized strain rate is defined as:

$$\beta = \frac{r \cdot H_0^2}{c_v} \quad (4)$$

where r = strain rate at which loading occurs and H_0 = initial specimen height.

β dominates the behaviour of the large strain solution: when this value is less than 0.1 the analytical solution can be approximated by the following expressions, defining the average, the drained face and the undrained face conditions:

$$\sigma'_{v(ave)} = \sigma_v - \frac{2}{3} u_b \quad (5)$$

$\sigma'_{vd} = \sigma_v$ (6)

$\sigma'_{vu} = \sigma_v - u_b$ (7)

The coefficient of consolidation is given by

$$C_v = \frac{H^2}{2u_b} \cdot \frac{\Delta\sigma'_v}{\Delta t} \qquad (8)$$

where $\Delta\sigma'_v$= change of effective stress in the time interval Δt.

The strains in the drained and undrained face are:

$$\varepsilon_{Ed} = \varepsilon_E + \frac{\beta}{3}\left[\frac{1}{1 - (\beta \cdot H)/3H_0}\right] \qquad (9)$$

$$\varepsilon_{Eu} = \varepsilon_E - \frac{\beta}{6}\left[\frac{1}{1 - (\beta \cdot H)/3H_0}\right] \qquad (10)$$

where $\varepsilon_E = \Delta H/H$.

Choice of the strain rate

The allowable loading rate is still open to discussion. This rate shoud be governed by the maximum allowable pore pressure ratio (PPR); this is the rate of the pore pressure over the applied stress. This pore pressure ratio should be large enough so that the adequate pore pressures are built up for the determination of C_v, but small enough so that large hydraulic gradients are not established. This is mainly due to the presence of the term u_b in the denominator of the equations for the calculation of C_v (i.e. Equations 2 and 8). A value of u_b equal to or approaching zero will cause the expressions to be meaningless. On the other hand, if pore pressures become excessive, assumptions made in deriving the theory will not be fulfilled because of the unknown distribution of pore pressures that are assumed, in general, parabolic.

The rate will depend primarily upon the permeability and compressibility of the soil. Several methods have been suggested for estimating the strain rate but none of them give satisfactory solutions for all possible soiltests. This test program tried to validate the proposed strain rate formulas for the reconstituted clay material.

TEST PROGRAM

Reconstituted kaolinite clay

The material adopted for the study is a reconstituted material due to the benefits of its homogeneity and reproducibility.

Following the experience of several researchers (Smith and Wahls, 1969 and Wissa et al, 1971), kaolinite clay was chosen which due to the internal structure has a low expansion, medium plasticity and is regarded as an inactive clay.

The commercially available dry powder was thoroughly mixed, reconstituted to a slurry at a water content well above the liquid limit and consolidated under a small pressure (around 40 kPa) in cylinders of 13 cm of diameter. This " slurry" method has many advantages and has been used even for the preparation of large specimens (McManus and Kulhawy, 1993).

After the preparation, the material was stored adequately in a humid room. For the tests, the samples were removed from storage and the actual test specimen was cut from the center of the 13 cm diameter cylinder to the appropriate size. This procedure tries to simulate the natural process of consolidation of soft soils and the specimens can be fabricated very close to full saturation with almost no segregation of fines.

Several classification tests were performed giving the following average index properties: water content = 35.0%, liquid limit = 48.0 %, plasticity index = 22.5 % and specific gravity = 2.61 t/m3. Following the Unified Classification System the soil can be classified as a *lean clay* with group symbol CL. The US Department of Agriculture System takes it as a *silty clay* and after the AASHTO Classification System it belongs to the group *A-7-6*.

The small scatter observed in the results of the classification tests proved the homogeneity and good quality of the material.

Experimental program

Results are presented from nine CRS consolidation tests performed using an automated Bristol CRD consolidation cell , four IL oedometer tests and one special IL test with pore pressure measurements and alternate permeability measurements (IL9), all on the reconstituted kaolinite clay.

The CRS tests performed can be devided in two sets. The first set includes all tests for studying the effects of strain rates (CRS3 to CRS9), the second group is devoted to study consolidation behavior around the preconsolidation pressure (CRS10 to CRS12). In the latter tests a load-unload cycle is performed in order to impose a known preconsolidation pressure of 100kPa.

Table 1 summarizes the general details of the tests with H_0 = initial height, d = diameter, e_0 = initial void ratio, w_0 = initial water content, σ'_p = preconsolidation pressure due to sample preparation, PPR_{max} = maximum pore pressure ratio adopted at an effective stress of 10 kPa, k_m = initial measured permeability.

Test	Strain rate (%/h)	H_o (mm)	d (mm)	e_o	w_o (%)	Range of σ'p (kPa)	PPRmax (σ'v = 10 kPa)[1]	Init. k_m 10^{-9} m/s	Mean Temp (°C)
CRS3	1.02	25	76	1.00	34.4	20-60	0.34	2.94	23.5
CRS4	1.02	25	76	0.99	34.7	20-50	0.33	2.32	21.5
CRS5	1.52	25	76	1.00	34.8	15-50	0.38	3.32	24.0
CRS6	2.27	25	76	1.01	35.7	15-50	0.58	2.68	24.0
CRS8	0.29	25	76	1.01	35.3	25-50	0.10	2.78	23.5
CRS9	3.77	25	76	1.02	35.3	12-40	0.67	3.26	25.0
CRS10	1.03	25	76	1.00	35.4	12-40	0.28	3.90	22.5
CRS11	1.03	25	76	1.01	34.9	12-30	0.30	4.53	21.5
CRS12	2.36	25	76	0.9	33.2	-	0.42	1.98	22.5
IL1	-	19	63	0.97	34.9	25-70	-	-	20.0
IL2	-	19	63	1.03	34.9	25-75	-	-	20.0
IL3	-	19	63	1.03	35.0	25-75	-	-	20.0
IL4	-	19	63	1.02	34.9	25-70	-	-	20.0
IL9	-	25	76	0.96	33.8	20-70	-	2.30	23.0

Table1 Summary of general consolidation characteristics of tests

A strict control of quality was applied to all tests. When faults or errors were detected, the test is rejected.

Experimental procedures

The CRS consolidation tests were performed using a computer-controlled, hydraulically loaded Bristol CRD cell. The automation of this device and detailed set-up procedures are described by Lopez (1997)

General guidelines for the test procedure are given in the standards. However, due to there importance, it is convenient to remark some aspects.

* The back pressure is applied in small increments (1 kPa/min or 0.01 bar/min). During the introduction of the back pressure, an adjustment of the axial load on the sample is necessary to compensate for the load produced by the back pressure on the load cell.

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[1] *Values adopted at an effective stress of 10 kPa.*

* Following a period of adjustment under full back pressure (between 6 to 12 hours, the time necessary to consolidate the specimen under seating load) the test is started. In that time, the sample height is kept approximately constant and the increase or decrease of the axial load is recorded.
* A short constant head permeability test is started by closing the valve that allows maintenance of the back pressure. A small differential pressure (approximately 7 kPa, following the suggestion of Armour and Drnevich, 1986) is applied to the base of the specimen. The water inflow is monitored with time by the pressure-volume controllers (GDS). When the inflow is more or less equal to the outflow, the coefficient of permeability is determined.
* The unloading may proceed at a constant strain rate. Normally, the same rate as for loading is used for unloading, taking care that negative differential pore water pressures do not go higher than the back pressure.

The standard IL tests were performed using the ASTM Standard D-2435-90. However, for the special IL test, conducted in the CRS cell, with alternate permeability tests and the monitoring of pore pressure, the procedure was very similar to the CRS tests:
Before the load is applied, the valve connecting the specimen base to the back pressure-maintaining device is closed to create a one-way drainage at the top of the specimen.
The load step is started at the same time of the manual application of a constant load.
The test data and results are monitored. The readings are recorded at the time values specified by the standard.
When the primary consolidation is finished, a short permeability test is carried out. The unloading may proceed after the last loading step. Normally, each successive load is one-fourth as large as the preceding one.

TEST RESULTS

This section synthesizes the results from the testing program and provides an analysis with regard to the stress-strain relationships, consolidation parameters and tests variables. In presenting the CRS results, a number of comparisons are made with IL tests as reference primarily because the test method is of widespread use in practice. The stress strain curves for IL tests were calculated both using the end of primary consolidation and the total deformation, showing almost no difference.
The IL results has been processed in function of Lagrangian strain and void ratio. As expected, they have similar results demonstrating the homogeneity of the samples. Additionally, the way for presenting stress-strain curves suggested by several researchers (i.e. Smith and Wahls, 1969) is adopted. Taking into account the void ratio change instead of any absolute value of

strains seems the best way for comparing the different curves. In such graph any difference in the slopes can be noticed.

The square root of time method (Taylor's method) and the log of time method (Casagrande's method) were adopted in the calculation of the coefficient of consolidation, C_v. In practice, large scatter is always found between methods (around 100% of the log t values) and this case is not an exception. If a third method is included (i.e. the method based on pore pressure measurements), even more scatter can be found. The general tendency is to use the $\sqrt{t}$ method for the unambiguous determination of the start and end of primary consolidation. However, in some loading steps problems occurred in defining the initial linear segment using this method, so the use of both methods was preferred in order to have a better approximation of Cv.

The back pressure effect

The use of back pressure in a consolidation test, can be analyzed based on the results of test IL9 which is performed in de CRS cell. The standard IL test, without back pressure, shows a slightly greater amount of compression for a given load than the test with the back pressure, which agrees with other findings (i.e. Lowe et al, 1964). This variation in compression is, however, within the normal range of variation between tests. Also back pressure can have an effect on the determination of preconsolidation pressure resulting in lower values than those obtained without using back pressure.

In relation to the C_v values, as seen in figure 1, a better agreement between the log t method and the $\sqrt{t}$ method is reached, confirming that the differences in both values may indicate the presence of air or the lack of a complete saturation of the sample and supporting the use of back pressure for consolidation tests on reconstituted soft clays. Accordingly the Cv values are slightly lower then the results of the tests without back pressure.
The effect of back pressure is also noticed on the compression index C_c (Figure 2) giving higher values in IL9.

Permeability test during IL

Olson (1986) suggested that the validity of the theory and fitting method can be checked by comparing a measured permeability k_m with the calculated permeability k_c out of the consolidation parameters. Test IL9 was performed with alternated constant head permeability tests following that suggestion.
The test confirmed that the permeability of the soil decreases with increasing compression and thus decreasing void ratio and that its variation in function of the vertical effective stress can be assumed as a straight line in a semi-log plot. Based on the good agreement between the

consolidation results of test IL9 with the other standard tests, it can also be concluded that the influence of a constant head permeability test with a small pressure gradient on the test results of IL9, is only minor.

It was shown by Olson that k_c from C_v obtained from Taylor's and Casagrande's method is almost always less than k_m . For test IL9 this is also true in relation to the CRS data, but the k_c values obtained from the other IL tests are slightly higher. This may be due to the different conditions between tests (i.e. back pressure, sample size, etc.).

CRS tests in comparison with IL tests

A major part of the study was dedicated to the strain rate effect in CRS testing on reconstituted clay. The strain rates suggested for CRS tests are normally between 0.01%/h and 3%/h (ASTM Standards). Practical experience showed that the optimum rate depends mainly on the characteristics of the soil and that slow rates are needed for soils with slow pore-water pressure dissipation. In the present study a strain rate range of 0.3%/h to 3.8%/h (see table 1) was covered.

A very good agreement can be noticed between the stress-strain curves obtained in the CRS tests for moderate strain rates and IL tests (Figure 3). The stress-strain curves from the CRS tests (Figure 4) show that the effective stress at any given void ratio change has a small decrease when strain rates increase. Strain rates seem to have an influence in the stress-strain curve at high strain rates, which is seen by the results obtained with test CRS9, where the stress-strain curve departs from the other curves.

In relation to the unloading curves at different strain rates shown in Figure 5, where for comparison purposes the common starting point was fixed at the beginning of unloading, some scatter is observed especially at low effective stresses (under 100 kPa). However, the dispersion obtained in the IL tests for the unloading curves is even greater. It seems as well that the strain rate slightly affects the results because at higher rates (i.e. CRS9) the negative change in void ratio is the highest.

The results of the coefficient of consolidation during compression (Figure 6) coincident, for the most part, with the lower boundary values obtained from IL tests for a given void ratio or stress. The comparison is done taken the minimum and maximum values obtained from tests IL1, IL2, IL3 and IL9 using both log t method and $\sqrt{t}$ method. However, the higher values of Cv out of IL tests are mainly influenced by factors such as sample size, lack of back pressure, lack of pore pressure readings, etc., because the lowest IL values also agree with the results from test IL9, which was performed with the same characteristics (ring dimensions and back pressure) as the CRS tests.

Figure 6 also shows that there is no noticeable effect on the C_v values for the different strain rates used. Most of the values lay inside the limits obtained from IL tests. At the very low rate (i.e. CRS8) the load frame did not run smoothly enough and the pore pressures were very small approaching the resolution limit of the differential pressure transducer. This accounts for some variations on C_v in slow rates and supports the recommendation of the standards to work with PPR > 3%.

As a conclusion, it appears that the strain rate within certain limits has no noticable effect on the consolidation parameters of remolded clays. These materials have a much weaker rate dependence than intact, cemented clays, confirming the suggestions of Sheahan and Watters (1997). For the material tested, the allowable rate of strains for obtaining results of good quality, were between 1%/h (i.e. CRS3) and 2.5%/h (i.e. CRS6).

The new version of the ASTM Standards states to select a strain rate that will cause the value of the excess pore-water pressure ratio to be between 3 and 30%. No additional suggestions are given and the choice of strain rate is left to the judgment of the engineer.

However, the analysis of the results and the PPR developed (see Figure 7) show that this suggestion is conservative because several tests developed higher PPR's but still showed good results (i.e. CRS6 and CRS5). This maximum PPR is developed at the beginning of the test and depends on the initial applied pressure. So to our opinion, the maximum PPR has to be related to a certain stress for comparison purposes. For simplicity an effective stress of 10 kPa has been adopted (see Table 1) as the reference value.

For evaluating the strain rate, Lee et al (1993) suggested to limit the dimensionless strain (β) to a value of 0.1. The β values obtained for some of the tests performed are shown in Figure 8. It can be seen that CRS9 is the only test that has values over the threshold. At the same time this is the test that showed less agreement in its results mainly at low effective stresses. This confirms Lee's conclusion that the dimensionless strain can be a good alternative over the PPR.

At the moment there are no criteria that allows the choice of a suitable strain rate beforehand. However, the best procedure seems to choose a rate with the help of any empirical method or based on experience and validate the results using the large strain theory. Remolded clays seem to have the advantage of a wide range of allowable strain rates. Further research is needed for other cases.

At the start of a CRS test a permeability measurement was performed in order to verify the trimming process. It was observed that the measured values did not significantly vary from the expected values. Also the small pore pressure gradient from the permeability test at the start of the loading phase is helpful in acquiring good consolidation parameters early in the test by the fact that steady state conditions are reached faster.

The coefficients of permeability calculated from the consolidation parameters are shown in Figure 9 together with the calculated values out of IL tests and the measured values out of IL9.

k_c values from CRS data agree very well with measured values (IL9), corroborating the good approximation of the consolidation parameters calculated. The approximation is much better than for IL testdata.

Non-linear Small Strain theory versus Large Strain theory

A comparison of the large strain theory solution with the non-linear small strain solution shows that both alternatives give almost identical results starting from a certain effective stress (Figure 10). In relation to the large strain theory, the convergence of the average, the drained face and the undrained face values show very clearly the point where the results get valid. An additional available parameter for the validation of the results is the normalized strain rate, β, which has to be less than 0.1. If both conditions are fulfilled, the results can be accepted. This is a big advantage in relation to the non-linear small strain theory. However, as part of the latter theory, a time factor T_v can be calculated and the condition when $T_v > 0.5$ can be determined delimiting the start point of steady state conditions which is, of course, strain rate dependent.

Preconsolidation pressure

A primary objective of consolidation tests is to determine the preconsolidation pressure, σ'_p, which is not well defined in remolded clays due to the lack of structure. Four tests were performed with an induced value of σ'_p of 100 kPa by preloading. The tests considered are IL4, CRS10, CRS11 and CRS12. It is important to mention that CRS10 and CRS11 have a strain rate of 1.0 %/h while CRS12 has a strain rate of 2.4 %/h. The results obtained are shown in Figures 11 and 12.

Figure 11 is showing the stress strain curves of the CRS tests in relation to IL4. The curves of the CRS tests are much more pronounced in the region of the preconsolidation pressure because of the better defenition of the curves. Having more points near the preconsolidation pressure implies less subjectivity to determine σ'_p.

There is also an indication of a decreasing value of σ'_p with increasing strain rates in accordance to other investigations (i.e. Hamilton and Crawford, 1959).

The samples tested showed some scatter during the first compression, but in reloading they present similar results in relation to the stress-strain curves, confirming the widespread procedure of load cycles to minimize the effect of sampling and disturbance.

In relation to C_v (figure 12), the values obtained in the range higher than 40 kPa are in the normal scatter and the approximation is fairly good. This value of 40 kPa is lower than the preconsolidation pressure and shows that it is possible to obtain valid consolidation parameters before reaching this preconsolidation stress. Nevertheless, it is worth to quote that near the preconsolidation pressure some of the assumptions of the CRS theory may not be valid like a parabolic distribution of pore pressure and a constant value of C_v between small strains.

Another way to validate the results before the preconsolidation pressure, is using the large strain theory. Although the convergence of the different solutions (drained face, undrained face and average values) is not as good as in the part beyond the preconsolidation pressure, it is possible to accept the results of CRS10 and CRS11 above 40 kPa. The case is not the same for CRS12 where the convergence is observed only above the preconsolidation pressure due to the higher strain rate.

CONCLUSIONS

An extended test program has been performed on remolded kaolinite clay to study the applicability and reliability of CRS tests. The following conclusions can be made based on the analysis of the results:

* The CRS results were found compatible to the standard IL tests although at lower boundaries of Cv. Most of the dispersion with the IL tests were found originating from the difference in sample size and the application of back pressure. The results of a special IL test performed with back pressure, alternate permeability tests and the same conditions (i.e. sample size, one way drainage, etc) as the CRS tests had an excellent agreement with the parameters derived from CRS tests, confirming this conclusion.
* The use of back pressure is very important in soft soils to assure full saturation of the sample.
*The study of strain rates confirmed the new hypothesis (Sheahan and Watters, 1997) that remolded clays have much weaker rate dependence than intact, cemented clays due to the lack of stress history. However, at very high or low rates the quality of results decrease.
* From all the available methods, Lee's criterion (1993) seems the most accurate to validate strain rates of CRS tests. The suggestion of limiting the maximum pore pressure ratio to 30% appears very conservative and seems to vary in relation to the type of soil tested and the stress history.
* The suggested procedure for the practical choice of a strain rate would be to choose a rate using an empirical method or supported by experience and validating the results using Lee's large strain theory (1981) observing the convergence of the different solutions (average values, drained face and undrained face) and limiting the maximum value of the normalized strain rate, β, to 0.1.
* Non-linear Small Strain theory (Wissa et al, 1971) and Large Strain theory (Lee, 1981) gave almost identical results. The latter theory has the advantage of showing graphically the range of validity of results.
* The set of tests performed to study the preconsolidation pressure confirmed that the calculated value is more accurate in CRS tests mainly due to the better definition of the stress-strain curve.

* An increased influence of the strain rate was observed in the tests with a previous loading cycle, confirming that the choice of the strain rates are much more critical in soils with stress history.
* The values of the coefficient of consolidation in the region close to the preconsolidation pressure were found less accurate, but still inside the normal dispersion range. Lee's large strain theory gives a good alternative to validate the results in this critical region.

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