Constant Rate of Strain Consolidation Tests on a Marine Clay from the Central Waters near Kau Yi Chau

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doi: https://doi.org/10.21467/proceedings.7.7.3

ABSTRACT

The constant rate of strain (CRS) consolidation tests offer several advantages over the conventional incremental loading oedometer tests. These include generating a continuous void ratio-effective vertical stress curve, completing a test typically within 2 days, full saturation of the specimen, and the ease of instrumentation for automated data collection. A new CRS testing system was recently established at the Public Works Central Laboratory, featuring full automation and accurate calibration. Different strain rate values were selected and applied in the CRS testing on undisturbed marine clay specimens from the Central Waters near Kau Yi Chau. Data analysis involved applying Wissa's modified linear theory to derive essential consolidation parameters. The study also examined the effects of strain rate on the void ratio-effective vertical stress curve, preconsolidation pressure, coefficient of consolidation, and base excess pore pressure, with initial findings presented in this paper.

1 INTRODUCTION

1.1 Historical notes

The constant rate of strain (CRS) testing technique, with specimens loaded continuously under controlled rates of strain, was first introduced by Hamilton and Crawford (1959) to better determine the consolidation characteristics of clayey soils. Strictly speaking, it is a constant rate of deformation test. Smith and Wahls (1969) demonstrated the detailed CRS test procedures and first established a mathematical model to interpret the test results, and a complete solution was achieved by Wissa et al. (1971) based on the small strain theory. Lee (1981) reviewed the model of Wissa et al. (1971) and proposed a moving boundary theory of consolidation that is suitable for both small and large strain conditions.

Gorman et al. (1978) conducted a sequence of CRS tests on three soil samples collected from Kentucky, the U.S., using strain rates ranging from 0.23–5.22%/hr. This study confirmed the reliability of the CRS test, for the results were comparable to those obtained from the conventional incremental loading (IL) oedometer tests and controlled gradient tests and showed that the CRS test required the shortest time (1.9 days on average) and was the easiest to perform. Further research by Gorman (1981) focused on the effect of strain rate on CRS test results and the strain rate selection scheme. It was suggested that the strain rate can be determined based on the soil's liquid limit and initial degree of saturation (Gorman, 1981). Leroueil et al. (1985) compared the results of a series of CRS tests on the Champlain Sea clay deposits of Eastern Canada with those of three other types of one-dimensional consolidation tests and discussed the strain rate effects on stress-strain relationship and preconsolidation pressure.

Proceedings DOI: 10.21467/proceedings.7.7; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-989164-3-3

The CRS test was studied and applied in Sweden as early as 1975 (Sällfors, 1975), and a Swedish national standard containing step-by-step instructions on the CRS test was released in 1991 (Svensk Standard, 1991). The Swedish standard recommends the rate of strain to be set to 0.0025 mm/min, which generates a deformation of roughly 18% in 24 hours for a 20 mm-high specimen (i.e., 0.75%/hr). If the tested specimen is very soft or muddy clay, a lower rate could be applied so long as the measured base excess pore water pressure u_b does not exceed 10% of the vertical total stress σ_v, yet u_b is allowed to be higher during some parts of the test, but not over 20% of σ_v (Svensk Standard, 1991, cited in Holm, 2016).

The American Society for Testing and Materials (ASTM) standardized the CRS test in 1982 with the designation D4186-82, which suggests the strain rate be selected based on the specimen's liquid limit, as shown in Table 1 (ASTM, 1982). The recommendation (ASTM, 1991) was revised in 1989 to maintain the absolute value of the base excess pressure ratio, $R = u_b/\sigma_v$, between 3% and 30% at any time during the test. In 2006, ASTM further changed the recommendation to keep an R value between 3% and 15% in the normally consolidated range during the loading phase of the test (ASTM, 2008). A Chinese standard on the CRS test can be found in the designation GB/T 50123-2019, where the method for estimating the strain rate is similar to the recommendation of ASTM D4186-82 (Chinese Standard, 2019). The International standard (ISO) or European standard (EN) for the CRS consolidation test is not available so far (as of 2024).

Table 1: Liquid limit-based strain rate selection for the CRS consolidation test suggested by the ASTM (1982) standard D4186-82.

Liquid limit (%)	Rate of strain (%/min) / (%/hr)
< 40	0.04 / 2.4
40–60	0.01 / 0.6
60–80	0.004 / 0.24
80–100	0.001 / 0.06
100–120	0.0004 / 0.025
120–140	0.0001 / 0.006

Some CRS tests conducted in Hong Kong were found in Premchitt et al. (1996) using the Rowe cell, aiming to determine the preconsolidation pressure of a stiff alluvial clay sample collected near the Chek Lap Kok airport. In this study, three strain rate levels of 0.3, 0.6, and 6%/hr were attempted, and the curves of void ratio, excess pore water pressure, coefficient of consolidation, and constrained modulus ($1/m_v$) against the logarithm of applied effective stress obtained under different strain rates were compared. However, though the plots clearly presented the strain rate effects on these consolidation parameters, the CRS test results in this report lack detailed interpretation. In addition, the limitations of the Rowe cell equipment when applied in the CRS test were not adequately analysed. Based on the assemblage of the Rowe cell, the stresses may not be uniformly distributed over the sample's cross-section, and the accuracy of the pore water pressure measurements was in doubt, which leads to errors when interpreting the test results using prevailing theories.

1.2 Characteristics of the CRS test

The CRS testing method offers several advantages over the conventional IL oedometer test. First, depending on the applied strain rate, the time required to complete a CRS test is usually significantly less than a conventional oedometer test. An IL oedometer test takes approximately two weeks, while a CRS test typically can be finished within two days.

Second, in conventional tests, a sequence of loading is applied to the specimen in discrete stages, so the consolidation properties at the applied pressures between loading steps can only be inferred. In contrast, the CRS test is performed as a continuous process, during which the vertical stress, axial deformation, and pore water pressure at the bottom of the specimen are measured continuously by the testing system. Hence, the CRS test results can be presented in practically continuous plots (e.g., the void ratio-effective vertical stress and pore water pressure-effective vertical stress curves), which favours more reliable estimates of the consolidation parameters, especially the preconsolidation pressure. It has been argued by Premchitt et al. (1996) that doing a

CRS test is probably the only way to accurately determine the preconsolidation pressure of stiff clays because the e-log σ'_v curve obtained from a conventional test would be too flat to identify the break in the curve.

Third, Stolle and Stolle (2011) pointed out that standard incremental loading tests generate high gradients of pore water pressure in the specimens that may not realistically develop in prototype applications. The CRS test, as an alternative approach, allows a smoother and more representative loading process, which is beneficial for characterising the consolidation parameters and minimizing sample disturbance.

Additionally, the CRS test can be instrumented to achieve full automation in terms of equipment setup, test procedures and data acquisition. The automation significantly enhances testing efficiency. The digitally recorded data are especially valuable for data analysis in research projects and streamline procedures in routine testing. By contrast, conventional oedometer testing relies on manual incremental loading which involves lifting the heavy metal discs onto the loading system, and manual recording data. These procedures are labor-intensive and prone to human error.

It is also worth noting that there is no provision for specimen saturation in the conventional oedometer tests. The specimen is merely soaked under a seating pressure of 5 kPa and assumed to be saturated during the test. In the CRS setting, a back pressure is applied to saturate the soil specimen, and this step is critical for accurately measuring the pore water pressure at the bottom of the specimen.

Though high-quality data can be obtained from the CRS test, a theory must be established before proceeding with the data reduction and interpretation, and the interpretation of the results requires more effort compared with the standard IL oedometer testing method. The IL oedometer test has long been a routine consolidation test with well-known and widely accepted methods and procedures to estimate the effective vertical stress, σ'_v, void ratio, e, coefficient of consolidation, c_v, hydraulic conductivity, k, coefficient of volume compressibility, m_v, and preconsolidation pressure from the results. However, the CRS test has been plagued by two major problems. One is that the distribution of (excess) pore water pressure throughout the height of the specimen varies, and the exact pattern, from zero at the drainage boundary at the top to a measured value at the bottom, is unknown, which poses challenges in calculating the average pore pressure and thus the average effective axial stress in the specimen. Another difficulty is selecting an appropriate strain rate at which to carry out the test for the type of soil specimen being tested. On one hand, a rate too fast would induce to much excess pore water pressure in the specimen so that results could not be interpreted correctly. On the other hand, if the deformation rate is too slow, the advantage of using the CRS test as a quick testing method is defeated, and it causes troubles in determining the primary consolidation properties due to the prominent secondary compression effects. Moreover, the excess pore water pressure generated under a very low strain rate is insignificant, causing problems in applying the equations for the consolidation parameters according to the available theories.

1.3 Theories of CRS result interpretation

The most popular theories for interpreting the CRS data are the linear theory of Smith and Wahls (1969) and the modified linear theory and nonlinear theory developed by Wissa et al. (1971). The theories of Wissa et al. (1971) was first adopted by ASTM. From 1982 to 2005, ASTM suggested the nonlinear theory to be used; since 2006, the modified linear theory has been recommended, with the equations of the nonlinear model provided in the appendix of the ASTM D4186, and the use of the nonlinear theory equations is not regarded as a non-conformance with the CRS test method.

The linear theory is established based on assumptions that the coefficient of volume compressibility, m_v, is constant, i.e., the relationship between the strain and effective stress is linear, and that the distribution of excess pore water pressure is linear throughout the height of the specimen. The nonlinear theory is based on assumptions that the virgin compression index, C_c, is constant, i.e., there is a linear relationship between the strain and log effective stress, and that the distribution of excess pore water pressure is parabolic.

The equations for estimating the effective vertical stress σ'_v, coefficient of consolidation, c_v, hydraulic conductivity, k, and coefficient of volume compressibility, m_v from CRS test are given in the latest version of ASTM D4186 under both linear and nonlinear models, with the linear model as the preferred method.

1.4 Research objectives

A CRS apparatus was recently procured by the Public Works Central Laboratory (PWCL) of GEO/CEDD. A collaborative research project was conducted by the Department of Earth Sciences of HKU and GEO with the following objectives:

(1) Assemble the apparatus with full automation and calibration;
(2) Establish the testing procedures based on the current ASTM (2020) standard D4186/D4186M–20$^{\varepsilon 2}$;
(3) Perform a series of trial tests on different types of soil with different specimen preparation: remoulded kaolin, reconstituted kaolin, remoulded kaolin with preconsolidation, and undisturbed marine clay obtained from the Central Waters near Kau Yi Chau;
(4) Study the data reduction and interpretation of the test results, including the application of linear and nonlinear equations provided in D4186/D4186M–20$^{\varepsilon 2}$; and
(5) Investigate the selection of appropriate strain rates and their impact on the interpretation of various consolidation parameters.

This paper presents some details of objectives (1) and (2) and some test results of undisturbed marine clay under objectives (3) and (4).

2 NEW CRS SETUP IN THE PUBLIC WORKS CENTRAL LABORATORY

2.1 Apparatus, test procedures and calibration

The new CRS testing system at the PWCL (Figure 1) is assembled using VJ Tech's TriSCAN-50 Pro Advanced Triaxial Load Frame, Multi-Purpose Consolidation Cell, and APC Pro Automatic Pressure Controller. It can be noticed from the schematic diagram in Figure 1 that the soil specimen, laterally constrained by the confinement ring, is submerged in the chamber together with a load cell that measures the axial force applied to the top of the specimen during the test. In each test, after the apparatus and soil specimen (cut and trimmed to fit the confinement ring and sandwiched by filter papers on its top and bottom) are assembled, the chamber is filled up with water, and a back pressure is applied to fully saturate the specimen. Then, the specimen is deformed axially at a constant strain rate (strictly speaking, a constant deformation rate), with drainage allowed only through its top boundary and excess pore water pressure measured at its base. A standard test comprises a loading phase, a holding phase (to allow the dissipation of base excess pressure), and an unloading phase. The axial deformation, axial load, chamber pressure, and base pressure at any time (t) during the test are measured automatically by the digimatic gauge, load cell and pressure transducers.

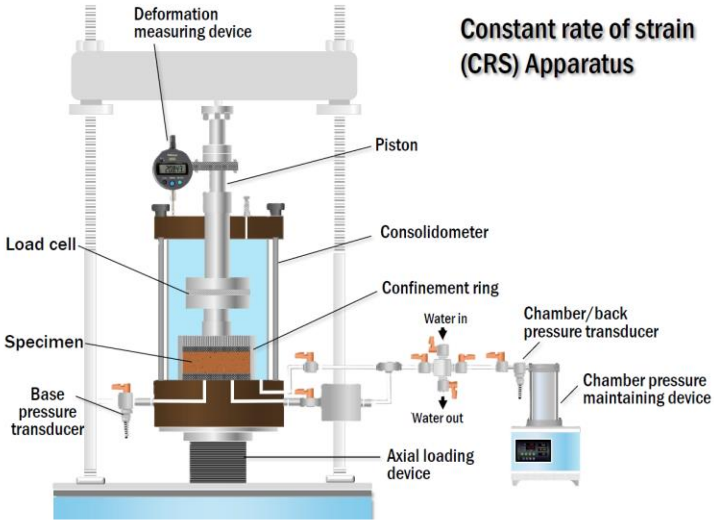



Figure 1: Photo and schematic diagram of the CRS testing apparatus at the Public Works Central Laboratory.

Most of the components of the CRS testing system were properly calibrated to meet the requirements of ASTM D4186 (clauses 6 and 7). In particular, the accuracy and capacity of the pressure transducers and load cell have been checked. In addition, the compressibility of the consolidometer during back pressure saturation and consolidation has been examined, and the magnitude of piston uplift force due to chamber pressure has been calculated to correct the axial force readings. The correctness and reliability of the data acquisition system has been carefully checked. The stability of the strain rate as provided by the system through the axial load device is discussed in Section 4 below. Some checking and calibrations may need to be repeated after a series of trial tests.

2.2 Data reduction

After completing the test, the net axial force, $f_{a,n}$, (kN) is obtained by correcting the system-recorded axial load with the piston uplift force, and the total axial stress, $\sigma_{a,n}$, in kPa is calculated by dividing $f_{a,n}$ with the specimen area. The axial strain rate at each time, $\dot{\varepsilon}_n$, is calculated as follows:

$$\dot{\varepsilon}_n = \frac{\Delta H_{n+1} - \Delta H_{n-1}}{H_0} \cdot \frac{1}{t_{n+1} - t_{n-1}} \quad (1)$$

where ΔH_n is the change in specimen height in cm obtained from the axial deformation records, and H_0 is the initial specimen height in cm.

The base excess pressure that is the difference between the measured base pressure and chamber pressure, in kPa at any given time is obtained as follows:

$$\Delta u_{m,n} = u_{m,n} - \sigma_{c,n} \quad (2)$$

where $u_{m,n}$ is the measured base pressure in kPa, and $\sigma_{c,n}$ is the measured chamber pressure in kPa.

Wissa et al (1971) provide the first complete solution to consolidation under CRS. The solution predicts an initial transient condition generated in the soil as the piston was set in motion and that must be dissipated before steady state conditions exist. They developed more general solutions that consisted of an initial transient portion and a steady-state portion. They also developed a dimensionless steady-state factor to show the degree of transience. The equations based on this modified linear theory for calculating various consolidation properties only apply to steady-state conditions. It can be shown that the Time Factor, T_v, is about 0.5 when the steady state factor is 0.4. The ASTM test method adopts this theory and specifies that the dimensionless steady-state factor F_n at each time is calculated as follows, to evaluate whether the transient strain at the start of a loading or unloading phase is small enough:

$$F_n = \frac{(\sigma_{a,n}-\sigma_{a,l})-(\Delta u_{m,n}-\Delta u_{m,l})}{\sigma_{a,n}-\sigma_{a,l}} \tag{3}$$

For any line of data with an F value less than 0.4, the calculation results of the steady state equations will be approximate, and the corresponding data is ignored. If F_n is greater than 0.4, the consolidation parameters will be calculated as follows.

The average effective axial stress, $\sigma'_{a,n}$, in kPa is obtained as:

$$\sigma'_{a,n} = \sigma_{a,n} - \frac{2}{3}\Delta u_{m,n} \tag{4}$$

where $\sigma_{a,n}$ is the total axial stress in kPa, and $\Delta u_{m,n}$ is the base excess pressure in kPa. It means that the excess pore water pressure follows a parabolic distribution.

The hydraulic conductivity, k_n, in m/s is calculated using the following equation:

$$k_n = \frac{\dot{\varepsilon}_n \cdot H_n \cdot H_0 \cdot \gamma_w}{2 \cdot \Delta u_{m,n}} \cdot \frac{1}{10000} \tag{5}$$

where γ_w is the unit weight of water at 20 °C, i.e., 9.7891 kN/m^3. H_0 and H_n are the initial and current specimen thicknesses respectively in cm. It may be noted that Equation (5) is a first-order approximation in the calculation of the average thickness of the specimen.

The coefficient of volume compressibility, $m_{v,n}$, in m^2/ kN is calculated as:

$$m_{v,n} = \frac{\varepsilon_{n+1} - \varepsilon_{n-1}}{\sigma'_{a,n+1} - \sigma'_{a,n-1}} \tag{6}$$

Then, the coefficient of consolidation, $c_{v,n}$, is obtained as:

$$c_{v,n} = \frac{k_n}{m_{v,n} \cdot \gamma_w} \tag{7}$$

Finally, the base excess pressure ratio, $R_{u,n}$, (dimensionless) is calculated as:

$$R_{u,n} = \frac{\Delta u_{m,n}}{\sigma_{a,n}} \tag{8}$$

3 TRIAL TESTS PROGRAMME

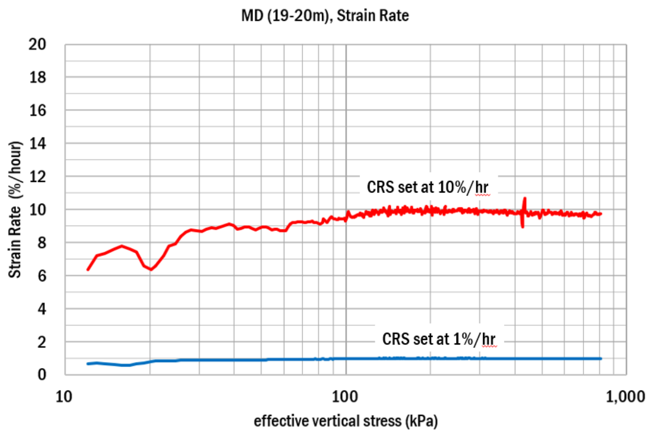
This study involves selecting two types of soil samples for conducting CRS and IL consolidation tests: kaolin and undisturbed marine deposits obtained near Kau Yi Chau (from a 100 mm Piston sample). The marine deposits consist of soft, dark grey silty clay. The kaolin samples are prepared using various methods, including remoulding, remoulding with applied preconsolidation pressure, and reconstitution. A comprehensive series of tests has been developed for these soils, considering different applied strain rates and back pressure rates. The testing program comprises approximately 20 CRS tests and 10 IL tests. This paper focuses on presenting preliminary test results of the undisturbed marine clay obtained at a depth of 19–20 m below the seabed surface. It includes two CRS consolidation tests conducted under strain rates of 1% and 10%. Additionally, the results of a traditional IL oedometer test are provided for comparison.

4 RESULTS AND DISCUSSION

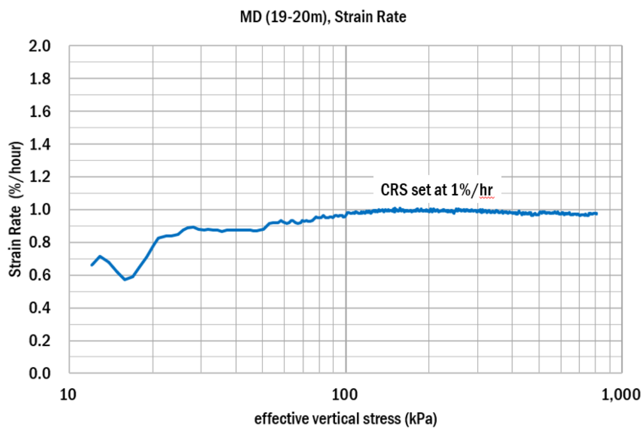
4.1 Strain Rate

Selecting an appropriate strain rate for the CRS test on a specific soil is a critical step in obtaining reliable and meaningful test data, which is also the main focus of Objective (5) in this research project. For the initial trial, we estimated the strain rate based on the marine clay's liquid limit and the method outlined in Table 1. With the sample's liquid limit at approximately 50%, a suitable strain rate of around 0.6%/hr was determined, leading to the selection of a 1%/hr strain rate in our trial run. Additionally, a higher strain rate of 10% was employed for comparison. Following the CRS test results, we evaluate whether the pressure ratio, $R = u_b/\sigma_v$, falls between 3% and 15% during the normally consolidated stage to assess the suitability of the strain rates (refer to discussions in Figure 7).

Although the accuracy of the applied strain rate has been confirmed through the proper calibration, we take the opportunity to assess the effectiveness of the automated system in providing and maintaining the chosen strain rate during the test. Figure 2 displays the results for the selected strain rates of 1%/hr and 10%/hr.



(a)



(b)

Figure 2: (a) Strain rates provided by the testing system during the tests; (b) provision of strain rate = 1%/hr.

It can be seen from Figure 2(a) that, for a selected strain rate of 10%/hr, the testing system is capable of providing 90% of the specified strain rate starting at σ′ = 30 kPa. We consider our automated testing system satisfies the ASTM D4186-82 requirement that the rate shall not have more than 10 % cyclic variation. For the selected strain rate of 1%/hr, at a first glance, Figure 2(a) may suggest better performance for a lower strain rate of 1%/hr. However, upon adjusting the vertical axis scale as displayed in Figure 2(b), it becomes apparent that the testing system actually performs similarly in delivering both selected strain rates.

4.2 Steady-state factor, F

As discussed in Section 2.2 above (see also Equation (3)), the equations derived from Wissa's modified linear theory to determine various consolidation properties are applicable only under steady-state conditions. ASTM standard specifies that the calculation of consolidation properties like k, m_v and c_v is considered valid if a minimum F value of 0.4 can be achieved. Figure 3 shows the variation of F with applied effective vertical stresses under two different strain rates. In Figure 3, the variation of F with applied effective vertical stresses is depicted for two distinct strain rates. It is evident that the steady-state factor remains above 0.9 throughout the test for both selected strain rates.

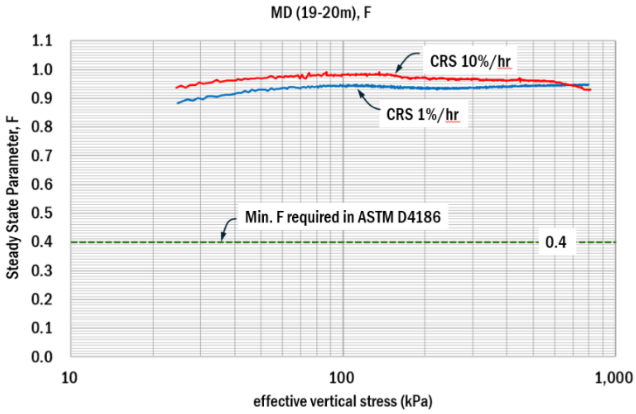


Figure 3: Variation of the steady-state factor, F, during the CRS tests.

4.3 *e-log σ′ plot and preconsolidation pressure*

The void ratio vs effective vertical stress plots for marine clay under three testing scenarios are shown in Figure 4. The CRS tests yield continuous curves, while the IL test results in discrete points that are then manually connected to form a smooth curve. The preconsoldiation pressures, σ'_0, for the three tests are estimated by the Casagrande's construction method and are shown also in the Figure. Given that the current effective vertical stress on the marine clay is around 175 kPa, it is intriguing to observe that Casagrande's method underestimates the preconsolidation pressures based on the test results illustrated in Figure 4. This discrepancy presents a puzzle that warrants further investigation.

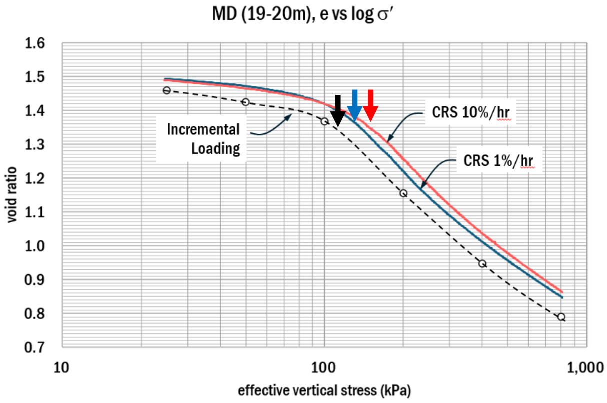


Figure 4: e-log σ′ curves for a marine clay obtained by the CRS tests and the IL test.

The range of the preconsolidation pressure may also be seen from the CRS test using the plots as shown in Figures 5 and 6. This provides one of the advantages of the CRS test over the conventional IL test to roughly estimate this parameter by different methods.

As far as the strain rate is concerned, as expected, the CRS test with higher strain rate gives a slightly larger σ'_0. With similar initial void ratio, the position of the curve from the IL test suggests that the average strain rate of this test is somewhat below 1%/hr.

4.4 Coefficient of consolidation

Proceedings DOI: 10.21467/proceedings.7.7

Series: AIJR Proceedings
ISBN: 978-81-989164-3-3
ISSN: 2582-3922

The coefficient of consolidation, c_v, from the IL test is estimated from the square root time plots for each incremental load. For the CRS test, the hydraulic conductivity and coefficient of volume compressibility are first calculated using Equations (5) and (6). Then the c_v values are computed from Equation (7), and the results are plotted in Figure 5. The results for the CRS test with a strain rate of 1%/hr and the IL test are illustrated more clearly in the right panel of the figure by adjusting the vertical axis scale.

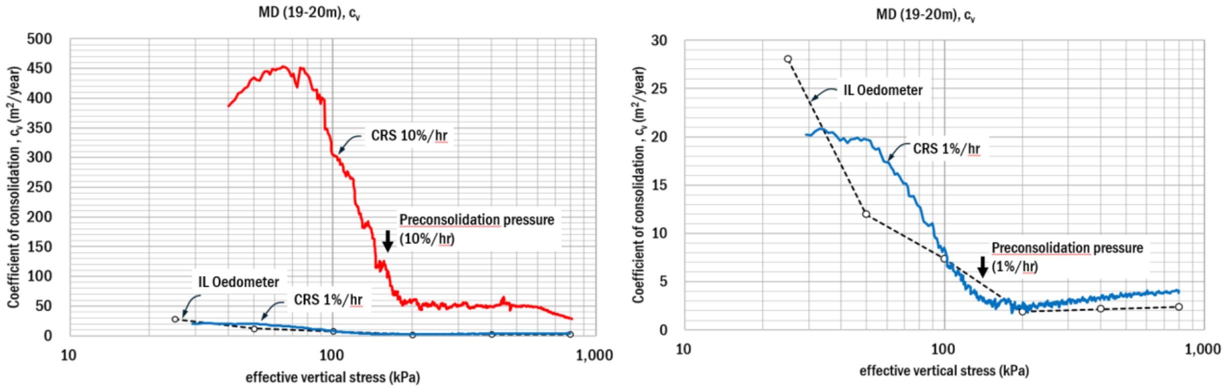


Figure 5: The coefficient of consolidation, c_v, obtained by the CRS tests and the IL test.

The coefficient of consolidation, c_v, values for the normally consolidated sections of the marine deposit, as determined from the CRS 1%/hr and IL tests, are similar, ranging from 2 to 4 m^2/year depending on σ'. However, the c_v values derived from the CRS 10%/hr test might be overestimated when utilizing a high strain rate. These findings underscore the significance of selecting an appropriate strain rate for a CRS test.

The test results presented in Figure 5 also highlight a well-established phenomenon: the coefficient of consolidation for over-consolidated clay are notably higher than those for normally consolidated clay. The drastic shift in c_v values, corresponding to changes in σ', indicates the position of the preconsolidation pressure.

4.5 Base excess pore pressure and base excess pressure ratio

The variation in base excess pore pressure with σ' is illustrated in Figure 6 for the CRS tests carried out at two distinct strain rates. The findings clearly indicate that as the clay sample transitions from the over-consolidated state to the normally consolidated state, the base excess pore pressure begins to rise. This observation aligns with the understanding that the coefficient of consolidation for normally consolidated clay is considerably lower than that for over-consolidated clay. Therefore, the CRS test provides an additional approach to approximately determine the preconsolidation pressure.

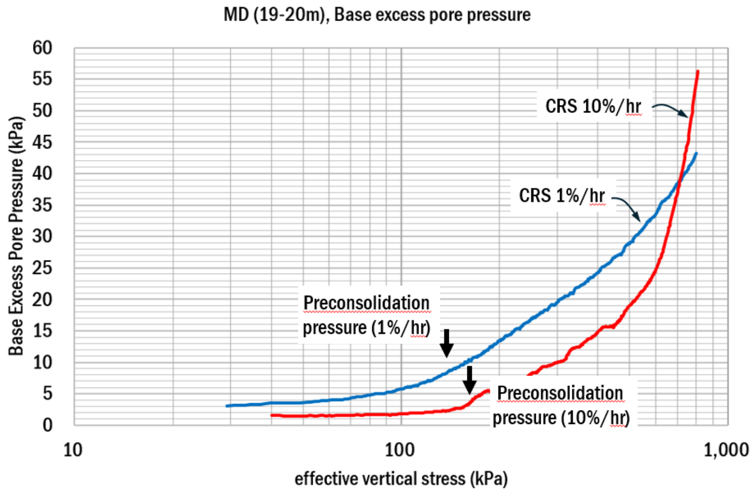


Figure 6: Variation of the base excess pore pressure during the CRS tests.

As discussed in Sections 1.1 and 4.1, the latest ASTM standard suggests selecting a strain rate that maintains the excess base pressure ratio, R (= u_b/σ_v), between 3% and 15% in the normally consolidated range during the test's loading phase. Figure 7 displays the outcomes for the two strain rates employed in the trial experiments. It is evident that the 1%/hour strain rate meets the ASTM standard, while the 10%/hour strain rate falls marginally within acceptable limits. The test results illustrated in Figures 3 to 7 strongly indicate that the 1%/hour strain rate is a suitable choice for the marine deposits under examination.

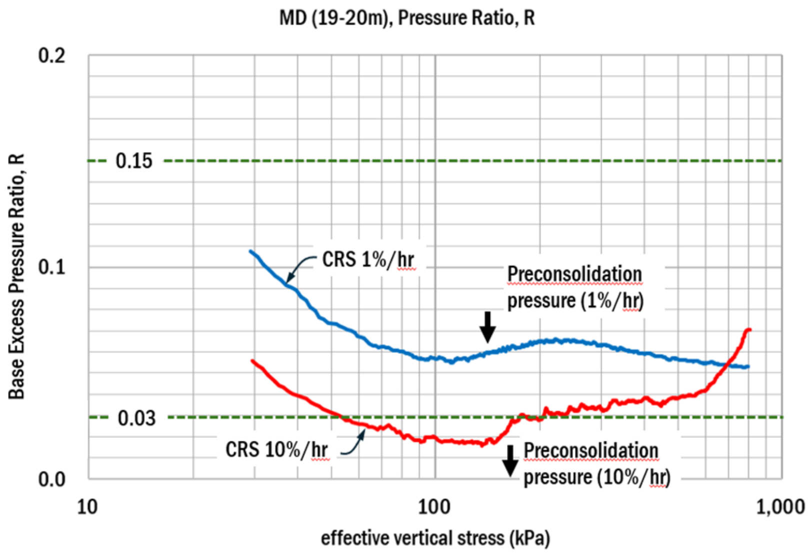


Figure 7: Variation of the base excess pressure ratio, R, during the CRS tests.

5 CONCLUSIONS

A newly automated CRS consolidation testing system has been successfully put together and calibrated. Trial examinations utilizing a marine deposit sample obtained close to Kau Yi Chau have been carried out to showcase that the testing system can be effectively employed for both routine and research-focused tests. A strain rate of 1% per hour has been determined to be suitable for this marine clay. Plots shown in Figures 5 and 6 are utilized to validate the preconsolidation pressures estimated through Casagrande's method. The coefficient of consolidation values, plotted against the effective vertical stress, are presented in Figure 5, along with a comparison to the discrete values obtained from the IL oedometer test.

ACKNOWLEDGEMENTS

We express our appreciation to the technical staff at the Public Works Central Laboratory for their invaluable support in this project. This paper is published with the permission of the Director of Civil Engineering and Development and the Head of the Geotechnical Engineering Office, the Government of the Hong Kong Special Administrative Region.

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