Application of a novel oedometer setup for performing constant-rate-of-strain (CRS) test on soft soils

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ABSTRACT
A Modified setup for automatic oedometer apparatus was designed at Université de Sherbrooke to perform constant-rate-of-strain (CRS) tests particularly for soft soils. The proposed setup can simultaneously be used to control the mechanical loading and pore-water pressure along with the measurement of the induced volume changes and interstitial pore-water pressure. The setup can also be employed to perform conventional incremental loading tests automatically. This paper describes the automated CRS oedometer setup in addition to the test procedure. Some preliminary results on soft clay obtained from CRS and conventional oedometer test are presented and compared herein. The results indicate that strain rate change affects the determination of pre-consolidation pressure and the compressibility indexes of soft clays.

RÉSUMÉ

Une cellule œdométrique modifiée a été conçu à l'Université de Sherbrooke afin de réaliser l'essai de consolidation au taux de déformation constante (CRS) sur les sols argileux déformables. Le montage proposé offre la possibilité de contrôler simultanément le chargement et la pression interstitiel en mesurant la déformation et la pression interstitielle en excès. Ce montage peut être utilisé pour faire les essais de consolidation par chargement incrémental. Cet article décrit l'appareil de consolidation au taux de déformation constante ainsi que le protocole d'essai. Des résultats préliminaires obtenus à partir du sol argileux sont présentés et comparés avec les résultats des essais de consolidation conventionnelle. Les résultats indiquent que le changement du taux de déformation affecte la pression pré-consolidation et les indices de compressibilité des sols argileux.

1 INTRODUCTION

Constant-rate-of-strain (CRS) oedometer test is an alternative testing approach compared to incremental loading (IL) method to estimate the volumetric characteristics and hydraulic conductivity of fine grained soils. CRS test has gradually gained popularity in comparison to the conventional oedometer test due to several advantages.

CRS test was first suggested by Hamilton and Crawford (1959) as a rapid method to obtain the pre-consolidation pressure along with the deformability indexes such as the compression and swelling indexes. The disadvantages of IL test including scattered measurement of stress-strain data points and its time-consumption have urged the practitioners to rely on CRS test. In addition, Leroueil et al. (1983a) indicated that due to step loading procedure of IL test, the amount of secondary compression can not be fully captured since this value changes with each loading and soil specimen. On the other hand, CRS has its own disadvantages such its inability to measure secondary compression due to continuous change in applied vertical strain. Similar to IL test, CRS test cannot address the problem of clay consolidation resulting from excess pore water pressure dissipation (Feng, 2010). The main challege in CSR test however, is to select a suitable strain rate prior to loading the soil specimen (Lee et al.,1993; Fox et al., 2014).

Ozer et al. (2012) stated that the allowable strain state applied to a specimen depends on the initial void ratio and thus, the compressibility of the soil. Since the gain or loss of structural stregnth in deformable materials is highly dependent on the pore-water pressure, it is required to employ a laboratory setup that provides not only the required sensitivity in measurement of volume changes but also the capability to keep track intersititial pressure (i.e. pore-water pressure) evolution.

This paper reports a modified automatic oedometer setup designed for performing CRS tests at Université de Sherbrooke which can measure vertical deformations as low as 0.02% during continuous measurements of pore-water pressure and the induced excess pore-water pressure. The device can also be used to perform automatic conventional IL tests. The paper highlights the performance of CRS test by presenting some experimental observations on soft clays. In addition, a comparison between the IL and CRS tests have been made regarding the effect of strain rate and interstitial pressure on the obtained stress-strain curves.

2 ON THE CHOICE OF ANALYSIS METHOD AND STRAIN RATE

Unlike IL tests where effective vertical stress is considered uniform throughout the specimen at the end of each consolidation step, in CRS tests, the unknown distribution of pore-water pressure makes it difficult to determine the effective vertical stress (Ozer et al. 2012). Various methods of analysis exist when it comes to obtaining the compressibility, hydraulic conductivity and coefficient of consolidation for CRS tests.

Recently, Fox et al. (2014) conducted an extensive research regarding the choice of data analysis approach. Based on their studies, for the cases at which the coefficient of compressibility a_v, is constant, the linear solution as in the formulation of current ASTM D4186/D4186M developed by Wissa et al. (1971) is sufficient to analyze the experimental results. However, when the compression index C_c, is constant, it was found that ASTM D4186/D4186M nonlinear solution induces analytical error for determination of hydraulic conductivity, k_h and the coefficient of consolidation c_v. In this regard, Eq. 1 to Eq. 4 show the steady state factor, average effective vertical stress, hydraulic conductivity and coefficient of consolidation respectively.

$$F = \frac{\log(\sigma_v - u_b) - \log(\sigma_{v0})}{\log(\sigma_v) - \log(\sigma_{v0})} \quad [1]$$

$$\sigma'_v = \left(\sigma_v^3 - 2\sigma_v^2 u_{ex,b} + \sigma_v u_{ex,b}^2\right)^{1/3} \quad [2]$$

$$k_{v,n} = \frac{-0.434.\mathrm{r}.\gamma_w.H_0 H_n}{2\sigma'_{v,n}.\log\left(1 - \frac{u_{ex,b,n}}{\sigma_{v,n}}\right)} \quad [3]$$

$$c_{v,n} = \frac{-H_0 H_n.\log\left(\frac{\sigma_{v,n+1}}{\sigma_{v,n}}\right)}{2(t_{n+1} - t_n)\log\left(1 - \frac{u_{ex,b,n}}{\sigma_{v,n}}\right)} \quad [4]$$

Where σ_v is applied effective vertical stress at a given strain level, σ_{v0} is the effective vertical stress at the beginning of the test, u_b is the excess pore-water pressure at the base of specimen. In addition, H_n is the height of specimen at a given time, n, $\sigma_{v,n}$ is the effective vertical stress at a given time, $u_{ex,b,n}$ is the excess pore-water pressure a given time t_n, while H_o and r initial height and strain rate respectively.

Based on formulation above, the choice of strain rate is critical parameter. A CRS test conducted at too high a strain rate cannot correctly be interpreted since it generally produces higher pre-consolidation pressure (Nash et al. 1992). Yet, too small strain rate may lead to problems in determining the consolidation properties. Consequently, the right r value should be somewhere between these two extremes. Normally, the strain rate value is set based on the variation of u_b/σ_v which is called the base excess pressure ratio. According to ASTM D4186/D4186M, this value should be limited to a value between about 3 % and 15 % at the end of the loading phase. However, Studies of Henriche and Belkacemi (2018) suggests that this range is strongly dependent on the value of initial void ratio and the specimen compressibility. As a result, the proper range of strain rate is also a matter of discussion. Since the selection criterion are often old or limited to certain type of soils, further studies regarding this subject is required. A proper laboratory tool can aid the researchers to better evaluate such behavior in order to develop more comprehensive criteria and to better understand the volume change charactersitics during CRS tests.

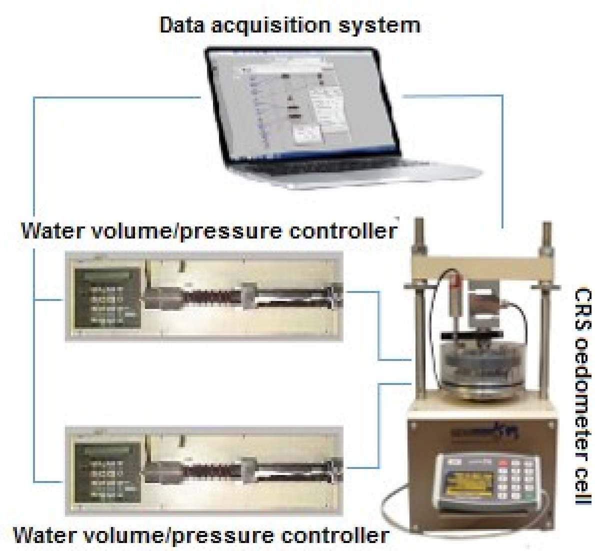

Figure 1. CRS oedometer setup

3 AUTOMATIC OEDOMETER SETUP

Figure 1 shows the layout of proposed oedometer setup in this study. The setup, using the GDS Instruments AOS frame, is designed to perform conventional IL test as well as saturation and loading/unloading phases of CRS test. The oedometer cell within the automatic loading frame is connected to two water volume/pressure controllers and a computer that enables the operator to control the test without any need of manual pressure changing after assembling the oedometer cell (GDSLAB software with custom interface). The volume/pressure controllers are employed to apply back pressure and measure the excess pore-water pressure during CRS loading stages (see Figure 1). The controllers were enterprise level volume/pressure controller (ELDPC series) manufactured by GDSinstrument Ltd., which maintain and target pressure or volume using a pressurized cylinder filled with de-aerated water in which the filling fluids are displaced by an actuated piston moving in the cylinder. The controllers can maintain a constant water pressure within the pressure range of 1 MPa or the measurement of water volume exchange with 0.15% accuracy in its full range.

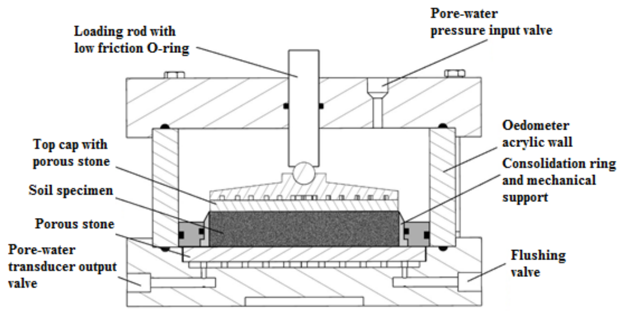

Figure 2. Layout of designed CRS oedometer cell

Compared to traditional hanging weight loading frames, the setup uses a self-contained stepper motor driven loading frame (loading ram), also manufactured at GDSinstrument Ltd., in which the frame's internal motor provides monitorable and controllable displacement with the accuracy of 0.1% within the 45mm range of displacement. As a secondary means to monitor the applied displacement, a linear variable displacement transducer (LVDT) that can capture displacements in the range of $\pm$5mm at full scale output is also installed on the frame. The S-beam load cell (DBBSM- series) are adopted to impose and measure the loads within the range of 10 kN with the accuracy of 0.15%. The loading frame along with water volume/pressure controllers are connected to a data acquisition software called GDSLAB.

The CRS oedometer cell as shown in Figure 2, was designed at Université de Sherbrooke so that the saturation and loading phases are done without the need to remove the cell from the loading frame. The cell is a modified version from another cell aimed at testing soils under unsaturated conditions with the axis translation technique (Maleksaeedi, Nuth, and Chekired 2016), in which the sample sits in an airtight chamber with controlled air and water pressures. The developed cell incudes a stainless steel top platen with a piston passing through a low- friction O-rings to ensure the vertical freedom of soil specimen during loading/unloading phases. A valve was installed on top platen through which the pore-water pressure can be applied and cell can be de-aired during saturation phase. The cell base consists of a water compartment with concentric pattern installed beneath a porous stone which is used for flushing the accumulated air bubbles during saturation phase through an exit valve. Using an input valve, the water volume/pressure controller is connected to the base platen in order to impose positive pore-water pressure to saturate the specimen in saturation phase and to measure the induced interstitial pressure during CRS loading/unloading phase. A special mechanical support was design to minimize the movement of sample ring during loading phase or the occurrence of excessive excess pore-water pressure beneath the specimen. The effective diameter of the cell base equals the diameter of sample ring which is about 65 mm, while the height of the surrounding rigid wall may vary depending on the desired height of the undisturbed or disturbed specimens from 10 mm to 50 mm. A rigid top cap attached to a porous stone was designed that simulates free drainage condition.

The oedometer cell was calibrated for compliance errors, including the movement of the loading ram, and to observe the leakage problem. It was observed that no leakage occurs by using the proposed setup which proves the prevalence of proposed oedometer cell to minimize the water leakage problem.

4 MATERIAL PROPERTIES AND TEST PROCEDURE

In this study, a series of oedometer tests were performed on undisturbed soft clay samples that were collected from a mining facility (location remains undisclosed for confidentiality purposes). All sampling Shelby tubes were carried to laboratory, paraffined and stored a humidity room to preserve their original water content. Two specimens, named herein IL1, IL2 were prepared and tested using conventional oedometer with hanging weight loading frame and two specimens, named herein CRS1, CRS2 were tested with CRS tests. The physical properties of L1/CRS1 and IL2/CRS2 clay samples are given in Table 1. In this table, w_N,G_s, PI stand for natural water content, specific gravity, and plasticity index while LP, LI, CI are plasticity limit, liquidity index and consistency index respectively.

Table 1. Physical properties of soft clay samples

Physical parameters	IL1/CRS1	IL2/CRS2
w_N	49.5%	52.5%
G_s	2.772	2.691
PI	43.0	32.0
LP	21.0	23.0
LI	0.7	1.0
CI	0.33	0.78

All specimens were extracted from Shelby tubes using standard extruder. Special care was taken to minimize specimen disturbance during extrusion and trimming. The samples were then extruded into a lubricated ring using a standard extruder. The consolidation ring used for the tests had a height about 19.0 mm and a diameter of 63.5 mm. After placing the soil specimens in the ring, any small voids were carefully filled with remolded soil without disturbing the specimen. The ring and soil specimens were weighted for unit weight and initial water content determination. Before oedometer tests, the initial height and weight of each specimens were measured to determine the initial unit weight, void ratio and water content respectively.

Employing conventional oedometer apparatus, IL1 and IL2 specimens were tested. After placing the specimens in the consolidation cell, the loading cap was carefully put on the specimens in order to transmit vertical loads. No filter paper was used to avoid enmeshment of fine soil particles with fibre of filter paper. The specimens were put under minimal stress before adding the distilled water at room temperature to the oedometer cell to saturate them. The IL1 specimen was subsequently loaded incrementally to 770 kPa. During each load increment, the settlement was monitored to decide when to proceed to the next load increment. For IL2 specimen, similar procedure as IL1 was followed yet, it was loaded to 1310 kPa and then unloaded to 155 kPa. Using the recorded settlements, the induced deformations under each vertical stress were calculated. After finishing the tests, the water content of specimens was measured and recorded.

Prior to performing each CRS test, the water compartment and porous stone of the designed oedometer cell were saturated with using distilled water. Afterwards, the ring with the specimen was placed on top of the porous stone with a filter paper and then, the mechanical support and rigid wall loading were placed. The CRS cell was next closed with rigid platen while the loading cap on top of the specimen covered with a filter paper.

After fixing the CRS cell on the loading frame, the specimens were slightly loaded to 40 kPa ensure the continuity between the soil specimen and consolidation ring. Connecting the water volume/pressure controller, a back pressure of 50 kPa lower than applied vertical stress was gradually imposed at the bottom of each specimen to reach a target effective vertical stress around 10 kPa and subsequently the cell was filled with de-aired water for saturating the specimens. Once reaching the target pressures, the specimens remained under constant vertical stress and pore pressure overnight. Periodically the CRS cell was flushed at the top to minimize the amount of trapped air in the cell and specimens. Then, for all CRS consolidation tests, the water volume/pressure controller connected through the top valve was set into the pressure control condition to impose the target pore-water pressure of 50 kPa while the other controller connected to the bottom valve was set into volume control condition to act as a pressure transducer to measure the induced excess pore water pressure during the loading/unloading phases. Using trial and error, strain rates of 5%/hr and 2%/hr were chosen for loading and unloading phases. Monitoring the induced excess pore water pressure, it was observed that these values did not surpass the maximum base excess pressure ratio recommended by ASTM D4186/D4186M which is an excess pressure less than 15% of the applied vertical stress. After completion of loading path, the induced excess pore water pressure was allowed to dissipate under virtually zero unloading strain ratel level (i.e. 0.0001%/hr). The specimens were loaded up to 1000 kPa and unloaded to 100 kPa while the induced excess pore pressures were continuously measured acquisition system at 10 second intervals.

5 RESULTS AND DISCUSSIONS

5.1 Comparison of IL and CRS tests

Figure 3a and 3b shows the variation of stress-strain curves obtained from both CRS and IL tests. As it can be seen, the CRS tests showed a gradual curvature compared to IL tests. Since CRS test provides more data points, it facilitates the interpretation procedure and reduces the judgment required in estimation of pre-consolidation pressure. Yet, in the absence of a solid criteria for determination of the pre-consolidation pressure, special care must be taken regarding the use of CRS test results. For instance, using Casagrande (1936) approach, the pre-consolidation pressure of each specimen were about 280 kPa, and 200 kPa respectively in the CRS tests. Preconsolidation pressure showed an increase compared to the values of IL test which were 270 kPa and 195 kP respectively (see Table 2). The difference in the obtained values is mainly attributed to effect of strain rate on the pre-consolidation stress and the evaluation method. It must not be looked as the superiority of CRS test in measurement of volume change characteristics compared to IL test. The yield stress obtained from IL test manifests the full stress history accumulated from changes in the effective stress and better represents the field conditions. However, the results herein confirm the findings of other researchers such as Vaid et al. (1979) and Nash et al. (1992) as they observed an increase in the apparent pre-consolidation pressure in CRS tests in comparison with IL tests. It must be noted that studies of Kirstein and Liu (2017) suggests that the Casagrande (1936) approach results in less accurate determination of pre-consolidation pressure compared to bilogarithmic approaches like Onitsuka et al. (1995) approach.

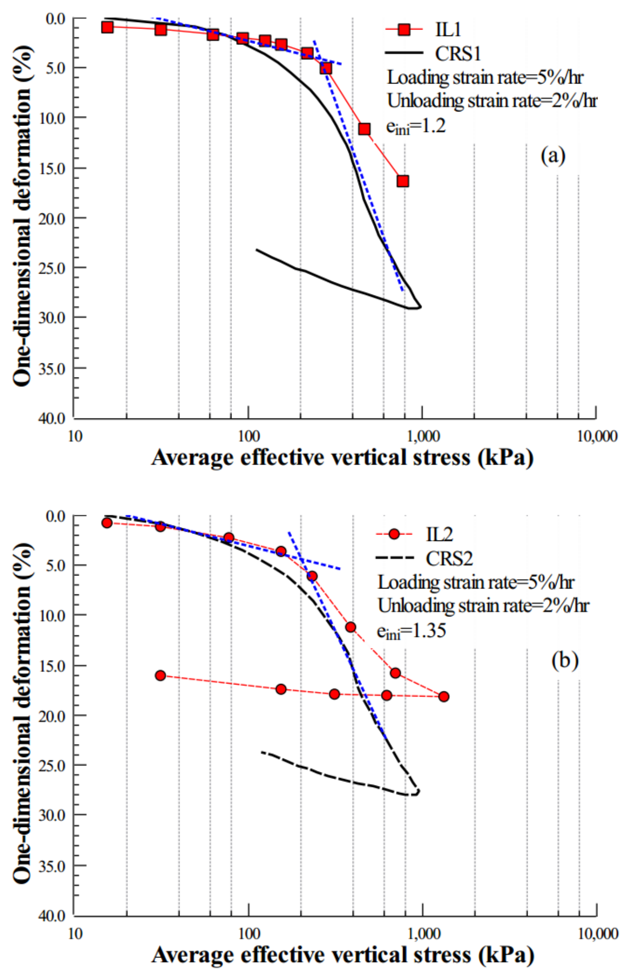

Figure 3. stress-strain curve of (a) CRS1 and IL1 (b) CRS2 and IL2

Moreover, studies of Holm (2016) suggests that Casagrande approach essentially generates higher pre-consolidation pressure and its use in evaluation of CRS test is questionable since it is designed for IL tests. Nevertheless, it is concluded that the strain rate might not have significant effect on the applicability of pre-consolidation pressure detemination methods. Further studies are required to develop a better representative evaluation method designed for CRS tests.

The data analysis also suggests that the steady state factor (F) for all three CRS tests were higher than 0.4 set by ASTM D4186/D4186M. The average values of this factor for CRS1, CRS2 were about 0.99 yet, it was observed that this value fluctuated and slightly decreased during the tests. Consequently, the transient condition was minimized and analysis can be continued as steady state condition using Eq. 2 to Eq. 4.

Figure 3 also confirms the findings of other researchers (Claesson, 2003; Jarad, Cuisinier, and Masrouri, 2017) regarding the shifting the stress-strain curves in the direction of increasing stresses at higher strain rate. However, it is also remarked that the deformation required for reaching the pre-consolidation pressure is independent of strain rate.

Although increase in compression index, C_c, due to increase in strain rate is well documented (Watabe et al. 2012; Watabe and Leroueil 2015), the strain rate dependency of swelling index, C_s, is less understood.

Table 2. Volume change characteristics of tested specimens

Specimen ID	σ'_p (kPa)	C_c	C_s
CRS1	280.0	0.103	0.066
CRS2	200.0	0.123	0.090
IL1	270.0	0.092	-
IL2	195.0	0.086	0.025

CRS2 specimen showed higher level of swelling compared to CRS1. Mesri et al. (1978) stated that the swelling index decreases with decreasing void ratio. However, this may be attributed to variation of excess pore-water pressure induced by mechanical loading as expressed in Figure 4. After complete dissipation of excess pore-water pressure, the deficiency in excess pore-water pressure (i.e. negative excess pore-water pressure) increased as average effective stress decreased for both CRS1 and CRS2. Such behavior is related to the soil skeleton rebounds which causes an increase in the total volume of specimen (Davis-Smith 2004). The decrease in excess pore-water pressure causes the water to seep back to the specimen and since the permeability of clays is generally low, throughout the unloading phase, the higher deficiency of excess pore-water pressure results in higher swelling.

In addition, in Figure 4, it was observed that during loading phase, the generated excess pore-water pressure of CRS2 was higher than CRS1. This is related to intrinsic low permeability of CRS2 compared to CRS1 as depicted in Figure 5. Due to lower permeability of CRS2 specimen, the excess pore-water pressure was generated more as the effective stress increased in comparison to CRS1.

Variation of coefficient of consolidation regarding for constant strain rate for tested CRS specimens are shown in Figure 6. Generally, the coefficient of consolidation, c_v, depends on the strain rate as stated by Gorman (1981) particularly in the initial steps of consolidation. Yet, as excess pore-water pressure decreases, average effective stress increases and then, the c_v values for CRS tests seems to converge.

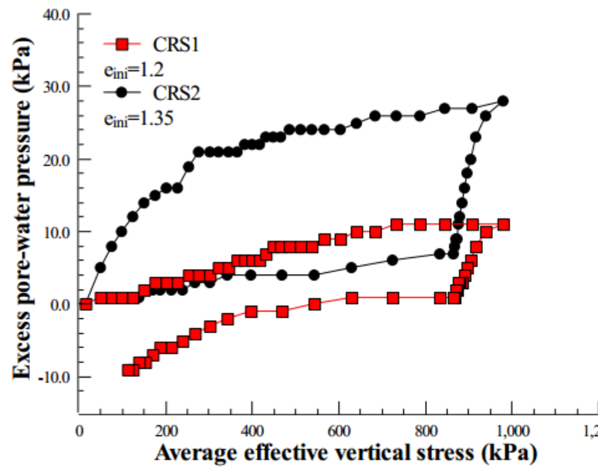

Figure 4. Variation of excess pore-water pressure with average effective stress for CSR1 and CSR2

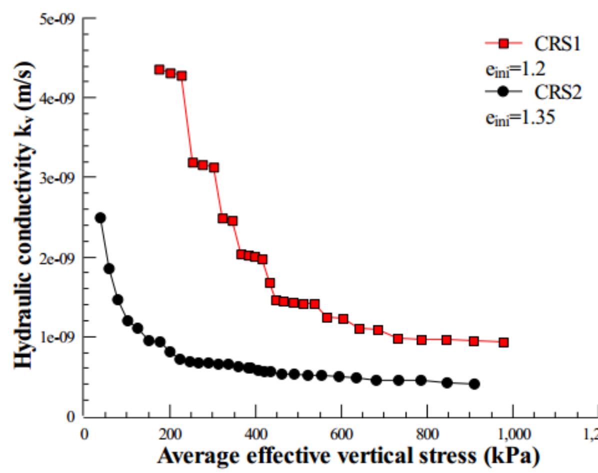

Figure 5. Variation of hydraulic conductivity with average effective stress for CRS1 and CRS2

The results herein supports the findings of Ferrari et al. (2016). They stated that the coefficient of consolidation decreases as effective vertical stress increases and reaches the yield stress while afterwards, it remains approximately constant beyond the the post-yield state. The obtained results also confirm the numerical evaluation of Henriche and Belkacemi (2018) indicating the fact that the base excess pore pressure ratio not only depends on the strain rate but also is strongly associated with the initial void ratio and the compressibilty. Based on the obtained results, it can be concluded that CRS test can be run with higher strain rate which saves both time and experimental efforts. However, a recommendation like this cannot be considered completely valid unless more extensive CRS tests are performed.

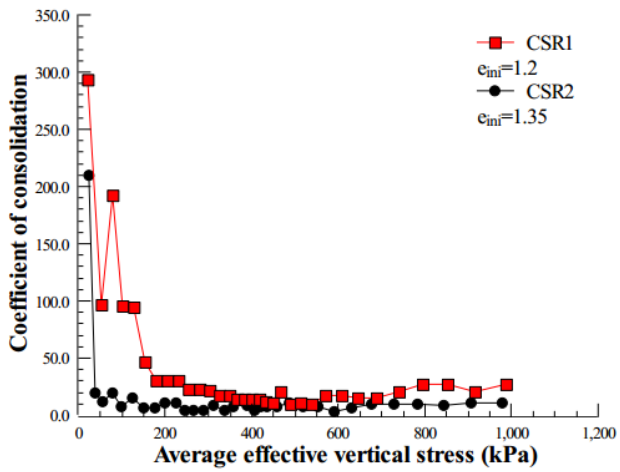

Figure 6. Variation of coefficient of consolidation with average effective stress for CSR1 and CSR2

6 CONCLUSION

A modified automatic oedometer apparatus was designed at Université de Sherbrooke to perform constant-rate-of-strain consolidation tests. The cell is designed in a fashion that is sensitive in measuring low deformation which is particularly of interest for soft clays. Using the proposed setup, a continuous measurement of both pore-water pressure and excess pore-water pressure is possible. The new setup is also suitable for performing conventional consolidation tests.

Using the novel CRS setup, a series of CRS tests were performed on soft clay to evaluate the base excess pore-water pressure ratio proposed by ASTM D4186/D4186M. For tested materials, it was observed that a strain rate as high as 5%/hr can induce excess pore-water pressure lower than 30% of applied effective stress which suggests strain rate depends on the degree of softness of tested soils.

The CRS tests results were also compared with conventional incremental loading tests. The results confirm the fact that the change in strain rate affects the measurement of pre-consolidation pressure and the volumetric characteristics such as compressibility index and coefficient of consolidation.

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