Canadian Geotechnical Journal
Revue canadienne de géotechnique

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Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2016-0203.R1
Manuscript Type:	Article
Date Submitted by the Author:	22-Oct-2016
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Keyword:	Clay, pre-consolidation pressure, consolidation test, Compressibility

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Draft

A revised paper submitted for review and publication in the Canadian Geotechnical Journal

October 2016

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Abstract

Shear strength and compressibility of fine-grained soils is strongly influenced by their stress history and the maximum (pre-consolidation) pressure (σ'_p). Accurate determination of σ'_p is thus critical for settlement and stability analysis involving fine-grained soils. Many graphical techniques are available for estimating σ'_p from the interpretation of soil compression in laboratory consolidation (oedometer) tests. However, the accuracy of these methods has not been extensively proven or compared with each other. A series of 30 laboratory oedometer tests is carried out in this study based on controlled-rate of strain and incrementally-loaded testing techniques. Several Canadian clay specimens are subject to cycles of one-dimensional compression loading and unloading in order to produce a known stress history and σ'_p . The imposed σ'_p are compared with the predictions of 11 methods for determining σ'_p . The accuracies of these methods are subsequently evaluated by comparing their predictions with σ'_p imposed during the consolidation experiments. While these methods mostly overestimate σ'_p , it is determined that a bi-logarithmic graphical approach based on the slopes of the virgin compression and recompression segments of soil compression curve provides the most accurate predictions of σ'_p . The potential ranges of errors associated with the application of each method are also presented.

Keywords: clay, pre-consolidation pressure, laboratory consolidation test, plasticity, compressibility

Introduction

Compressible fine-grained soils often exhibit a memory of the past stress history which they have experienced. This memory of soils is often presented by the pre-consolidation pressure corresponding to the maximum effective stress ever experienced by a particular soil (Becker, et al. 1987; Burland, 1990; Casagrande, 1936). Different stress histories can be naturally generated from a soil's geological stress history, soil erosion, desiccation, excavation, melting of glaciers, cementation, and sustained seepage forces.

Pre-consolidation pressure (denoted here by " σ'_p ") is a pseudo-elastic limit which separates 'elastic' pre-yield from 'plastic' post-yield behaviour of a soil. This is a key parameter in geotechnical engineering for analyzing and predicting settlement behavior, overconsolidation ratio, stress history, and short-term stability problems in soft clays (Jamiolkowski, et al. 1985; Ladd and Foote 1974; Mesri and Godlewski 1977; Wroth 1984). The results of these analyses could be questionable if there is significant uncertainty and inaccuracy in determining the value of σ'_p . Therefore, a reliable method that would provide accurate estimates of σ'_p is central to geotechnical engineering analysis and design in fine-grained soils.

Pre-consolidation pressure is often determined from the results of one-dimensional consolidation tests ("Oedometer tests"). Numerous empirical methods have been developed in the past for interpreting σ'_p of compressible soils from standard oedometer tests (Becker et al. 1987; Boone 2010; Burland 1990; Butterfield 1979; Casagrande 1936; Jacobsen 1992; Janbu 1967; Jose, et al. 1989; Oikawa 1987; Onitsuka et al. 1995; Pacheco Silva 1970; Sridharan 1991; Wang and Frost 2004). This study presents a comprehensive evaluation of the accuracy of these methods for interpreting σ'_p based on a large set of controlled-rate of strain (CRS) and incrementally-loaded (IL) consolidation tests on clay specimens with known stress histories. This is different than

some other investigations in which the pre-consolidation pressure was unknown or limited comparisons were made based on indirect estimations of σ'_p from undrained strength or other empirical methods (Boone 2010; Schmertmann 1955; Wang and Frost 2004).

Empirical Methods for Predicting σ'_p

The current approaches for determining soil pre-consolidation pressure from oedometer consolidation tests are all based on graphical interpretation procedures of void ratio (e) versus effective vertical stress (σ'_v) data. Table 1 provides a brief summary of these methods and their application procedures. While the classical method of Casagrande (1936) is based on fitting consolidation data with a bilinear void ratio and $\log(\sigma'_v)$ curve, several other investigators have proposed alternative forms of semi- or bi-logarithmic graphs for determining σ'_p . Compared to semi-logarithmic plots, plotting void ratio and σ'_v in a bi-logarithmic scale (Butterfield 1979; Oikawa 1987; Onitsuka, et al. 1995) can be advantageous by producing better linear relationships between $\log(1+e)$ and $\log(\sigma'_v)$. Note that although Sridharan et al. (1991) proposed an equal approach to that of Oikawa (1987), but here reference is made to Oikawa (1987) because of its earlier development.

As soil stiffness evolves from small strains to large strains near σ'_p , Janbu (1967) suggested determining σ'_p based on the reduction of constrained modulus (M) at σ'_p . Since lateral strains are prevented in an oedometer test, constrained modulus can be directly calculated from the ratio of load increment ($\delta\sigma'_v$) to the increment of volumetric strain ($\delta\epsilon_{vol}$). Janbu (1967) does not specify the detailed procedure for determining σ'_p , although some clarification is provided by Lunne et al. (2008).

Becker et al. (1987) suggested the concept of using the amount of strain energy (i.e. work) imposed on a soil specimen for determining σ'_p from oedometer consolidation tests. In this method arithmetic linear relationships are approximately fitted for the cumulative work applied per unit volume of a specimen (i.e. strain energy) and effective stress data from consolidation tests. The pre-consolidation pressure is defined at the point of intersection of the initial fitted line and the linear relationship observed at higher stresses. More recently, Wang and Frost (2004) suggested to use plastic (irrecoverable) deformations (instead of the total deformation) in order to magnify the contrast between soil consolidation behavior before and after σ'_p and employ the slope of the unloading-reloading curve to reduce sample disturbance effects. They show that the dissipated strain energy provides a better representation of soil yielding and hardening behavior. As summarized above, based on the parameters selected for plotting and presenting consolidation data, the existing methods for determining σ'_p can be categorized into four broad groups of: A) semi-logarithmic, B) bi-logarithmic, C) constrained modulus, and D) strain energy (work) procedures. All of the aforementioned methods implicitly assume that a particular soil exhibits a unique relationship between void ratio and σ'_v at the end of primary consolidation (Mesri and Choi 1985; Schmertmann 1955).

Experimental Procedure

A comprehensive series of 23 controlled-rate of strain (CRS) and 7 incrementally-loaded (IL) one-dimensional consolidation tests were carried out on two Canadian clay soils. CRS tests were employed to apply a continuous and controlled consolidation load on a soil specimen and provide a more precise measurement of soil consolidation behavior (Sheahan and Watters 1997). In order to build-in a known σ'_p , the specimens were subjected to cycles of consolidation loading

to a predetermined σ'_p , unloading and then reloading. The details of the experiments are described below.

Tested Clays

A number of block samples of Port Colborne and Sombra silty clays and several thin-walled tube samples of another silty clay from North Toronto were tested in this study. Laboratory tests including Atterberg limit, sieve analysis, and hydrometer tests were carried out on these samples according to the ASTM standard procedures (ASTM 2007,2010). Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analyses were also conducted on several specimens in order to determine their composition and mineralogy. Based on these analyses, it was determined that Port Colborne and Sombra clay samples were essentially composed of Kaolinite and Illite particles, whereas the North Toronto silty clay was mostly made of carbonates, followed by feldspar, quartz, Kaolinite, and Illite particles. As shown in Table 2, plasticity indices (PI) of the samples range from 9 to 24, with initial water contents (ω_0) of 19% to 52%. According to the Unified Soil Classification System (ASTM 2011b), the samples were low plasticity clays (CL).

Specimen Preparation

Trimming of the specimens to fit the consolidation ring was carefully done using a wire saw to minimize sample disturbance. A stainless steel consolidation ring (50 mm in diameter and 19 mm height) was then pushed slowly onto the specimens from its sharp edge. The inside surface of the consolidation ring was lubricated with low-friction silicon grease in order to minimize friction and specimen disturbance. A straightedge with a sharp cutting edge was used for the final trim and leveling both top and bottom surfaces of the specimen. Any small voids were carefully filled with remolded soil without disturbing the specimen. The consolidation ring and

the soil were then carefully weighed for the accurate computation of void ratio at the beginning of each test. Excess soil was also used for determining water content and soil classification. Finally, a thin disc fitted on the consolidation ring was used to push the top surface of the specimen about 2 mm into the ring in order for the porous stone and the loading cap to properly seat on the specimen. The porous stones were saturated by boiling them in water for about 20 minutes prior to specimen preparation.

IL Tests

In order to minimize the effect of secondary compression and the development of quasi-preconsolidation pressure (Leonards and Altschaeffl 1964; Mesri and Shahien 1994), incrementally-loaded (IL) consolidation tests were conducted following Method B of the ASTM standard procedure (ASTM 2011a). In these experiments, the axial stress was applied by dead weights via a lever ratio of 10 to 1. The magnitude of the axial stress was increased stepwise at a load-increment ratio (LIR) of 1 and each load increment was sustained for 60 minutes at which the specimen deformation reached a stabilized low rate (indicating the completion of primary consolidation as determined from log-time constructions). Since the duration of secondary compression was minimized by adopting short (60 minutes) load increment durations (instead of 24 hours waiting periods typically used in consolidation testing), the void ratio at the end of each load increment was used for constructing a consistent End-of-Primary (EOP) consolidation diagram as recommended by the ASTM standard procedure.

CRS Tests

CRS tests were carried out using an automated computer-controlled apparatus (manufactured by GEOTAC TRAUTWEIN, Texas, USA) following the ASTM D4186 standard procedure (ASTM 2012). The CRS apparatus includes an axial loading frame, a servo-controlled axial loading jack, pore water pressure and displacement (LVDT) transducers, and a CRS consolidation cell. After specimen preparation, the CRS cell was filled with deaired water for the application of cell pressure and the bottom pore pressure transducer was flushed and saturated to measure excess pore water pressure. A back-pressure was then applied in order to saturate the specimen. Prior to consolidation loading, the base drain valve was closed and the initial pore water pressure was recorded to evaluate specimen saturation. A pore pressure parameter (B) value of 98% or higher was achieved in all experiments. The specimen was subsequently consolidated by applying an axial load at a constant-strain rate while time, axial deformation, normal stress, and specimen base pore water pressure were measured. According to the ASTM standard method (ASTM 2012), a strain rate should be selected to produce a base excess pore pressure ratio of 3% to 15% at the end of the loading phase in order to measure hydraulic conductivity and the coefficient of consolidation. Therefore, trial tests were performed in order to determine the appropriate strain rate for each soil type. As a result, Port Colborne and Sombra clay specimens were loaded at constant strain rates of 1.5%/hr and 0.5%/hr, respectively. However, because of the high carbonate content, lower PI, and relatively more permeable specimens of the North Toronto silty clay, very little excess pore pressure developed even at a higher strain rate of 5%/hour. Greater strain rates ($> 5\%/hr$) however were not employed in order to comply with the ASTM standard (ASTM 2012) and avoid strain rate and dynamic loading effects. Moreover, hydraulic conductivity and coefficient of consolidation measurements were not required for this study.

Imposing Pre-consolidation Pressures

In both CRS and IL experiments, the specimens were loaded beyond their in-situ pre-consolidation pressures ($\sigma'_{p,o}$) and therefore the effects of $\sigma'_{p,o}$, in-situ fabric, and sample disturbance on the results of this study were eliminated. A pre-consolidation pressure ($\sigma'_{p,i} > \sigma'_{p,o}$) was built-in by maintaining a load for a period of 2 to 3 hours in order to complete primary consolidation and ensure full dissipation of excess pore water pressure. The specimens were unloaded and then consolidated (reloaded) to stresses exceeding $\sigma'_{p,i}$. This procedure was repeated for some specimens in order to produce different $\sigma'_{p,i}$ and evaluate the predictive methods for multiple magnitudes of $\sigma'_{p,i}$. The ensuing consolidation behavior would thus reflect soil compressibility behavior without any effects of stress relief or fabric disturbance (Schmertmann 1955). Minor corrections were also made to account for equipment deflection (for CRS and IL tests) and piston uplift force (for CRS tests). At the end of the experiments, each specimen was unloaded, removed from the consolidation cell and its final mass and moisture content were determined.

Experimental Results and Interpretations

Table 3 summarizes the characteristics of the experiments, and Figs. 1 and 2 present typical end-of-primary consolidation (EOP) $e - \log(\sigma'_v)$ stress paths from the CRS and IL consolidation tests of this study. The graphical procedures of Table 1 are used to estimate the pre-consolidation pressures (σ'_p). For consistency, the same ranges of σ'_v are chosen for recompression and compression segments (and their tangents) for each method. The pre-consolidation pressures (σ'_p) estimated for the experiments of Table 3 are summarized in Tables 4 to 6. As examples, the

applications of the graphical procedures of Table 1 are illustrated for CRS (for specimen P1) and IL (for specimen P7) tests in Figs. 3 and 4. Note that Janbu's procedure is quite sensitive to the slope of the $\sigma'_v - \varepsilon_{vol}$ curve for determining M . As a result of the limited data points (in IL tests) and the large variation of M with subtle changes in the slope of the $\sigma'_v - \varepsilon_{vol}$ curve (in CRS tests), fitting of straight lines to the $M - \sigma'_v$ plot was quite subjective and the determination of σ'_p became inconclusive for the soils of this study.

Discussion

Figs. 5 to 7 compare the imposed $\sigma'_{p,i}$ with those predicted by the empirical procedures for each category of Table 1. CRS and IL consolidation tests data from several other studies (Becker et al. 1987; Grozic, et al. 2003; Grozic et al. 2005; Jose et al. 1989; Sridharan 1991) are also included in these figures in order to supplement the analyses of this study and extend the comparisons to a wider range of PI (= 9 – 87). The absolute errors for each predictive method are presented according to the following equation:

$$\text{Absolute Error}(\%) = |\sigma'_p - \sigma'_{p,i}| \quad [\text{Eq. 1}]$$

In which, σ'_p and $\sigma'_{p,i}$ are the predicted and imposed (measured) pre-consolidation pressures, respectively. In general, as shown in Figs. 5 to 7, all methods tend to overestimate σ'_p which can lead to an unsafe stability analysis or the underestimation of consolidation settlement of structures overlying compressible clay deposits.

These plots further indicate comparatively higher inaccuracies in predicting σ'_p of samples with lower PI. This is due to the greater ambiguity in identifying the point of maximum curvature of

these samples. For example, as illustrated in Fig. 2(b), a rounded curvature was observed in the $e - \log(\sigma'_v)$ consolidation plot of North Toronto silty clay specimen (PI = 11.0) which produced a relatively gentle transformation from recompression to virgin compression behavior compared to the Port Colborne clay specimen (PI = 14.8) in Fig. 2(a). The lack of a sharp curvature obscured the point of significant change in consolidation behavior and hence σ'_p . More plastic clays (higher PI) exhibit sharp curvatures in $e - \log(\sigma'_v)$ diagrams with well-defined breaks at the vicinity of σ'_p and this would produce an overall higher degree of accuracy.

In order to facilitate comparison of the overall accuracies of the methods employed in this study, the magnitudes of errors are aggregated using the Root Mean Square Error (RMSE) as below:

$$RMSE = \sqrt{\frac{\sum_1^n (\sigma'_{p,i} - \sigma'_p)^2}{n}} \quad [\text{Eq. 2}]$$

RMSE presents the standard deviation (residuals) of the differences between σ'_p and $\sigma'_{p,i}$ (Hyndman and Koehler 2006). Table 7 ranks the overall accuracies of the methods analyzed here based on each method's RMSE from both IL and CRS test results. The ranges and average magnitudes of errors ($\sigma'_p - \sigma'_{p,i}$) are also provided for comparison, which can be used as a guideline for reporting the possible overestimation (positive error) or underestimation (negative error) of σ'_p determined from each of the empirical methods. Fig. 8 further provides a clearer comparison of the RMSE and average errors for all methods.

According to Table 7 and Fig. 8, the first seven methods (Becker, et al. 1987; Boone, 2010; Burland 1990; Butterfield 1979; Jose et al. 1989; Oikawa 1987; Onitsuka et al. 1995) show more-or-less comparable errors in predicting σ'_p , with the Oikawa (1987) and Burland (1990)

procedures providing the lowest overall RMSE and average error, respectively. These methods provided more accurate estimations of σ'_p (with lower average errors and RMSE), and hence their applications would be safer and more conservative. In fact, careful examination of data in Tables 4 to 6 indicates that these procedures (in particular Oikawa, Onitsuka et al. Butterfield, and Boone methods) provide similar estimates of σ'_p . Previous studies (Boone 2010; Grozic, et al. 2003; Jose et al. 1989; Onitsuka et al. 1995; Sridharan 1991) have often compared the accuracy of some of these methods based on different recompression and compression ranges of σ'_v for each method and they have proposed an apparently improved graphical method using biased ranges of recompression and compression segments to show a higher accuracy. Whereas in this study, precisely the same recompression, compression, and maximum curvature points (for Casagrande and Jacobsen methods) are consistently used with all methods in order to make an unbiased comparison of σ'_p estimates.

The aforementioned methods are followed by Casagrande (1936), Pacheco Silva (1970), and Wang and Frost (2004) techniques with increasing RMSE and average errors. Note that σ'_p estimated based on Jacobsen's method displayed extremely large errors and they are not shown in the histograms of Fig. 8. Among the work/energy methods (in Fig. 7), Becker et al.'s method provides better predictions of σ'_p (with an average error of 15.6 kPa) compared to the newer and updated method of Wang and Frost (2004) displaying an average error of 23.5 kPa. Note that despite the smaller average error (= 15.6 kPa) of Becker et al.'s method, its greater range of deviation (164.1 to -43.2 kPa) leads to its poorer overall RMSE and accuracy. Moreover, although Casagrande's method (with an average deviation of 33.1 kPa) is often recommended in most textbooks, codes (ASTM 2011a), and laboratory manuals, the accuracy of its predictions are among the lowest. The inferior accuracy of Casagrande's and Jacobsen's procedures is

particularly associated with their high emphasize placed on data points close to σ'_p where the $e - \log(\sigma'_v)$ curve displays it's greatest non-linearity. As a result, the perceived point of maximum curvature of the $e - \log(\sigma'_v)$ data and hence the determination of σ'_p become dependent on the scale of the void ratio axis. The higher inaccuracy of Jacobsen's method is not surprising considering its arbitrary suggestion of σ'_p equal to 2.5 times the stress at the point of maximum curvature of the $e - \log(\sigma'_v)$ diagram. These can significantly limit the confidence and reliability of σ'_p determination from these approaches, in particular by less experienced analysts and engineers. However, all of the other methods are free of these defects as they do not require the maximum curvature point.

Furthermore, as compared in Fig. 8, the continuous compression curves from CRS tests were generally effective in reducing the amount of errors in most methods. However, a number of methods (Boone 2010; Butterfield 1979; Pacheco Silva 1970; Wang and Frost 2004) show particularly greater errors in predicting σ'_p from IL tests than those from CRS tests. These methods are thus better suited for interpreting CRS tests which provide continuous data (compared to limited load increments in IL tests). On the other hand, Oikawa (1987), Jose et al. (1989), and Becker et al. (1987) exhibit similar performances in predicting σ'_p from CRS and IL tests.

It is finally noted that cementation bonds and aging may develop during and after sedimentation in the field, and produce an apparent preconsolidation effect and increase the in-situ preconsolidation pressure (Lunne et al. 2006). On the other hand, disturbance during sampling, transportation and laboratory specimen preparation could partly destroy the effects of aging and cementation. Hence sample disturbance could partly compensate the general overestimation of

σ'_p by the predictive methods examined here. Although, precise quantification of sample disturbance effects can be difficult and variable.

Conclusions

The accuracies of 11 methods for interpreting pre-consolidation pressure from laboratory consolidation tests were evaluated in this study. A total of 30 controlled-rate of strain (CRS) and incrementally-loaded (IL) consolidation tests were carried on three Canadian silty clays. Compared to incremental loading, CRS tests provided significantly more data points which facilitated the interpretation procedures and improved their overall prediction accuracy. The comparisons indicated that all methods would mostly overestimate σ'_p , which can reduce the conservatism of settlement or stability analysis in fine-grained soils. The overall accuracy of σ'_p predictions improved with increasing plasticity (PI) because of the sharper curvature of the consolidation curve, and hence the higher confidence in detecting the point of maximum curvature from consolidation data.

The accuracies of σ'_p predictions from different methods were compared based on the aggregated root mean square errors (RMSE) as well as the averages and the ranges of errors for each method. Among the 11 methods examined in this study, a bi-logarithmic graphical technique suggested by Oikawa (1987) was found to provide the most accurate predictions of σ'_p with an average overestimation potential of 16.8 kPa. According to this method, σ'_p is simply established from oedometer tests at the intersection point of tangent lines to the recompression and compression segments of soil compression data in a $\log(1+e)$ versus $\log(\sigma'_v)$ plot. Oikawa's method therefore provided an ideal combination of simplicity, quick interpretation and improved accuracy, and it is recommended in this study for determining σ'_p . This was verified by the

extensive database of one-dimensional consolidation experiments on several clay samples in this study. Next to Oikawa (1987), a number of other bi-linear plotting methods also provided close estimates of the known pre-consolidation pressures. On the other hand, Casagrande (1936) classical method provided relatively inaccurate predictions of σ'_p , with an average deviation of 33.1 kPa. The average and the ranges of errors established in this study further provide an opportunity to recognize the potential inaccuracy of each method and devise adequate safety factors for settlement or stability analysis.

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Figure Captions

Fig. 1: EOP consolidation curves for CRS consolidation tests P1 and S1 and the imposed pre-consolidation pressures ($\sigma'_{p,i}$)

Fig. 2: EOP consolidation curves for IL consolidation tests P7 and T5 and the imposed pre-consolidation pressures ($\sigma'_{p,i}$)

Fig. 3: Applications of (a) Casagrande (1936) and Jacobsen (1992), (b) Boone (2010) and Pacheco Silva (1970), (c) Burland (1990), (d) Butterfield (1979), (e) Oikawa (1987), (f) Jose et al. (1989), (g) Onitsuka et al. (1995), (h) Becker et al. (1987) and Wang and Frost (2004) methods for estimating σ'_p in CRS specimen P1 subjected to $\sigma'_{p,i} = 98.3$ kPa

Fig. 4: Applications of (a) Casagrande (1936) and Jacobsen (1992), (b) Boone (2010) and Pacheco Silva (1970), (c) Burland (1990), (d) Butterfield (1979), (e) Oikawa (1987), (f) Jose et al. (1989), (g) Onitsuka et al. (1995), (h) Becker et al. (1987) and Wang and Frost (2004) methods for estimating σ'_p in IL specimen P7 subjected to $\sigma'_{p,i} = 150.0$ kPa

Fig. 5: Comparisons of (a) $\sigma'_{p,i}$ with predictions, and (b) the ranges of absolute errors with PI for the semi-logarithmic methods

Fig. 6: Comparisons of (a) $\sigma'_{p,i}$ with predictions, and (b) the ranges of absolute errors with PI for the bi-logarithmic methods

Fig. 7: Comparisons of (a) $\sigma'_{p,i}$ with predictions, and (b) the ranges of absolute errors with PI for the strain energy methods

Fig. 8: Comparison of (a) RMSE and (b) average errors of different methods in predicting σ'_p from CRS and IL tests.

(a)

(b)

Fig. 1: EOP consolidation curve for CRS consolidation tests P1 and S1 and the imposed pre-consolidation pressures ($\sigma'_{p,i}$)

142x223mm (300 x 300 DPI)

(a)

(b)

Fig. 2: EOP consolidation curve for IL consolidation tests P7 and T5 and the imposed pre-consolidation pressures ($\sigma'_{p,i}$)

142x223mm (300 x 300 DPI)

Fig. 3: Applications of (a) Casagrande (1936) & Jacobsen (1992), (b) Boone (2010) & Pacheco Silva (1970), (c) Burland (1990), (d) Butterfield (1979), (e) Oikawa (1987), (f) Jose et al. (1989), (g) Onitsuka et al. (1995), (h) Becker et al. (1987) & Wang and Frost (2004) methods for estimating σ'_p in CRS specimen P1 subjected to $\sigma'_{p,i} = 98.3$ kPa

273x387mm (300 x 300 DPI)

Fig. 4: Applications of (a) Casagrande (1936) & Jacobsen (1992), (b) Boone (2010) & Pacheco Silva (1970), (c) Burland (1990), (d) Butterfield (1979), (e) Oikawa (1987), (f) Jose et al. (1989), (g) Onitsuka et al. (1995), (h) Becker et al. (1987) & Wang and Frost (2004) methods for estimating σ'_p in IL specimen P7 subjected to $\sigma'_{p,i} = 150.0$ kPa

273x387mm (300 x 300 DPI)

Fig. 5: Comparisons of (a) $\sigma'_{p,i}$ with predictions, and (b) the ranges of absolute errors with PI for the semi-logarithmic methods

142x224mm (300 x 300 DPI)

Fig. 6: Comparisons of (a) $\sigma'_{p,i}$ with predictions, and (b) the ranges of absolute errors with PI for the bi-logarithmic methods

141x223mm (300 x 300 DPI)

Fig. 7: Comparisons of (a) $\sigma'_{p,i}$ with predictions, and (b) the ranges of absolute errors with PI for the strain energy methods

141x223mm (300 x 300 DPI)

Fig. 8: Comparison of (a) RMSE and (b) average errors of different methods in predicting σ'_p from CRS and IL tests.

142x224mm (300 x 300 DPI)

Table 1: Summary of methods for predicting σ'_p from consolidation tests data

Method	Procedure basis	Reference
Semi-logarithmic	Intersection of tangent to virgin compression data with bisector of the angle between horizontal and the tangent line at the maximum curvature of the $e - \log(\sigma'_v)$ plot	Casagrande (1936)
	In-situ void ratio and tangent to the virgin compression line in $e - \log(\sigma'_v)$ diagram	Pacheco Silva (1970)
	Intersection of linear fit lines to the virgin compression and recompression segments voids index, $I_V = (e - e_{100})/C_c$ versus $\log(\sigma'_v)$ where e_{100} is void ratio at $\sigma'_v = 100$ kPa	Burland (1990)
	$2.5 \times$ (stress at the point of maximum curvature on the $e - \log(\sigma'_v)$ curve)	Jacobsen (1992)
	Intersection of the tangent line at the maximum compression index and the line parallel to the recompression line at the in-situ σ'_v	Boone (2010)
Bi-logarithmic	Intersection of linear fit lines of $\ln(I+e)$ and $\ln(\sigma'_v)$ plotted on linear scales	Butterfield (1979)
	Intersection of linear fit lines of $\log(I+e)$ versus $\log(\sigma'_v)$	Oikawa (1987)
	Intersection of linear fit lines to $\log(e) - \log(\sigma'_v)$ curve	Jose et al. (1989)
	Intersection of linear fit lines to $\ln(I+e)$ and $\log(\sigma'_v)$	Onitsuka et al. (1995)
Constrained modulus	Marked drop of constrained modulus with σ'_v in a linear scale	Janbu (1967)
Strain energy (work/unit volume)	Sharp increase of total strain energy density with increasing σ'_v	Becker et al. (1987)
	Graphical construction of dissipated strain energy versus effective vertical stress. Dissipated strain energy calculated from the subtraction of elastic strain energy from total strain energy.	Wang and Frost (2004)

Table 2: Basic characteristics of the clay samples used in this study

Clay	Silt (%)	Clay (%)	LL	PL	PI
Port Colborne clay	93.3	6.7	35.1	20.3	14.8
Sombra clay	71.0	29.0	46.0	22.0	24.0
North Toronto clay	55 – 87	12 – 45	32 – 48	11 – 23	9 – 23

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Table 3: Characteristics and σ'_p imposed in the experiments of this study

Test	Soil	Specimen	ω_o (%)	Test No.	Imposed $\sigma'_{p,i}$ (kPa)
CRS	Port Colborne clay	P1	26.9	1	98.3
				2	218.6
				3	330.0
		P2	32.2	1	107.5
				2	208.4
		P3	31.7	1	147.2
				2	319.4
		P4	30.3	1	87.8
				2	193.6
				3	315.7
		P5	40.2	1	109.8
				2	211.5
				3	363.6
				4	516.2
		P6	26.8	1	106.5
				2	260.1
				3	412.9
	Sombra clay	S1	34.3	1	106.7
				2	318.1
				3	522.3
IL	North Toronto Clay	T1	32.5	1	101.4
		T2	30.9	1	103.3
		T3	28.3	1	100.9
	Port Colborne clay	P7	19.4	1	150.0
	North Toronto Clay	T4	35.4	1	273.2
		T5	33.2	1	385.7
		T6	31.0	1	350.0
		T7	39.5	1	273.2
		T8	28.4	1	275.0
		T9	51.7	1	300.0

Table 4: Summary of pre-consolidation pressures obtained using the semi-logarithmic predictive methods

$\sigma'_{p,i}$ (kPa)	PI	σ'_p (kPa)				
		Boone (2010)	Burland (1990)	Casagrande (1936)	Jacobsen (1992)	Pacheco Silva (1970)
98.3	14.8	102	102	104	243	103
218.6	14.8	222	222	236	559	226
330.0	14.8	326	326	361	808	342
107.5	14.8	104	104	120	245	112
208.4	14.8	220	217	234	521	224
147.2	14.8	144	144	170	370	159
319.4	14.8	303	310	311	400	328
87.8	14.8	94	94	103	242	95
193.6	14.8	195	195	203	377	204
315.7	14.8	318	318	353	731	350
109.8	14.8	101	101	117	193	109
211.5	14.8	217	217	246	521	238
363.6	14.8	378	378	373	669	389
516.2	14.8	520	521	534	1027	539
106.5	14.8	122	122	134	262	124
260.1	14.8	261	263	278	615	270
412.9	14.8	413	415	447	894	450
106.7	24.0	110	110	129	292	114
318.1	24.0	257	258	267	366	282
522.3	24.0	520	523	525	985	518
101.4	10.0	158	158	179	255	194
103.3	10.0	106	106	108	269	105
100.9	12.0	223	221	246	191	270
150.0	14.8	174	174	200	375	197
273.2	19.0	357	358	380	342	426
385.7	11.0	436	436	518	964	461
350.0	15.0	308	308	350	875	313
273.2	23.0	337	332	357	546	343
275.0	12.0	307	307	332	688	312
300.0	22.0	283	283	286	750	283

Table 5: Summary of pre-consolidation pressures obtained using the bi-logarithmic predictive methods

$\sigma'_{p,i}$ (kPa)	PI	σ'_p (kPa)			
		Butterfield (1979)	Jose et al. (1989)	Oikawa (1987)	Onitsuka et al. (1995)
98.3	14.8	103	104	103	103
218.6	14.8	222	224	224	223
330.0	14.8	329	329	328	327
107.5	14.8	105	106	105	105
208.4	14.8	222	223	221	221
147.2	14.8	145	147	145	145
319.4	14.8	303	305	303	304
87.8	14.8	94	95	94	94
193.6	14.8	195	196	195	195
315.7	14.8	319	320	319	319
109.8	14.8	102	103	102	102
211.5	14.8	219	219	218	218
363.6	14.8	379	380	379	379
516.2	14.8	523	526	523	523
106.5	14.8	122	124	123	123
260.1	14.8	263	262	263	261
412.9	14.8	414	417	415	414
106.7	24.0	112	113	112	112
318.1	24.0	259	261	259	259
522.3	24.0	522	524	521	522
101.4	10.0	165	174	165	165
103.3	10.0	108	109	107	107
100.9	12.0	229	241	228	228
150.0	14.8	176	181	176	176
273.2	19.0	364	373	364	364
385.7	11.0	448	466	448	448
350.0	15.0	309	310	309	309
273.2	23.0	343	373	344	344
275.0	12.0	309	313	309	309
300.0	22.0	285	288	286	286

Table 6: Summary of pre-consolidation pressures obtained using the strain energy predictive methods

$\sigma'_{p,i}$ (kPa)	PI	σ'_p (kPa)	
		Becker et al. (1987)	Wang and Frost (2004)
98.3	14.8	102	102
218.6	14.8	223	221
330.0	14.8	336	335
107.5	14.8	110	111
208.4	14.8	224	221
147.2	14.8	152	148
319.4	14.8	316	306
87.8	14.8	96	93
193.6	14.8	199	198
315.7	14.8	329	328
109.8	14.8	109	108
211.5	14.8	227	224
363.6	14.8	383	382
516.2	14.8	534	533
106.5	14.8	128	139
260.1	14.8	266	264
412.9	14.8	423	424
106.7	24.0	115	114
318.1	24.0	275	275
522.3	24.0	531	525
101.4	10.0	206	205
103.3	10.0	107	106
100.9	12.0	265	264
150.0	14.8	187	187
273.2	19.0	399	400
385.7	11.0	525	522
350.0	15.0	316	316
273.2	23.0	336	337
275.0	12.0	318	318
300.0	22.0	282	283

Table 7: Comparison of accuracy and RMSE values of the empirical methods evaluated in this study

Accuracy ranking	Method	No. of Analysis	Average Error (kPa)	Error Range (kPa)	RMSE
1	Oikawa (1987)	55	16.8	127.1 to -59.2	33.2
2	Burland (1990)	34	11.6	120.3 to -60.6	34.1
3	Boone (2010)	30	11.7	210.0 to -60.7	36.6
4	Onitsuka et al. (1995)	34	13.1	127.3 to -59.0	36.8
5	Jose et al. (1989)	45	16.8	139.9 to -57.1	37.7
6	Butterfield (1979)	31	15.8	127.8 to -59.0	40.3
7	Becker et al. (1987)	58	15.6	164.1 to -43.2	41.2
8	Casagrande (1936)	75	33.1	145.4 to -50.7	44.3
9	Pacheco Silva (1970)	34	23.9	168.9 to -36.6	49.5
10	Wang and Frost (2004)	31	23.5	163.5 to -43.5	52.5
11	Jacobsen (1992)	30	276.9	578.7 to -48.3	317.7