Predicting consolidation coefficient of soft clay by time-displacement-velocity methods

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ABSTRACT

The coefficient of consolidation is a parameter, governing the rate at which saturated clay undergoes consolidation when subjected to an increase in pressure. The rate and amount of compression in clay varies with the rate that excess pore water pressure is dissipated; and hence depends on clay permeability. Over many years, various methods have been proposed to determine the coefficient of consolidation, c_v, which is an indication of the rate of foundation settlement on soft ground. However, defining this parameter is often problematic and greatly relies on graphical techniques, which are subject to some uncertainties. This paper initially presents an overview of many well-established methods to determine the vertical coefficient of consolidation from the incremental loading consolidation tests. An array of consolidation tests was conducted on fully-saturated and undisturbed clay samples retrieved by an oil-operated sampler, collected at various depths from a site in Nakdong river delta, Busan, South Korea. The test results on these soft sensitive clay samples were employed to predict the settlement rate of Busan clay. To establish the relationship of time-displacement-velocity, a total of 3 method groups from 10 common procedures were classified and compared together. Detailed discussion on the results of this study is also provided.

Keywords: Sensitive clay; coefficient of consolidation, incremental loading, velocity method, slope method

1 INTRODUCTION

Over many years, several methods have been proposed for determining the coefficient of consolidation c_v which indicates the velocity of vertical consolidation or settlement of foundation on soft ground. However, defining this parameter is often problematic and profoundly relies on graphical techniques that are subject to some uncertainties. In this paper, the authors' focus is mainly on the methods using the incremental loading (IL) consolidation tests. From the database of consolidation tests, the development of soil mechanics in many decades experienced numerous proposals to define c_v from either the earliest one, Taylor's (1948) method to the recent modified slope method published by Al-Zoubi (2015). However, these methods can generally be divided into three groups based on 3 plots including (1) time-displacement, (2) time-velocity, and (3) velocity-displacement, which are shown in Table 1.

2 SAMPLE PREPARATION AND CONSOLIDATION TESTS

The testing site of the study is located in the floodplain of the Nakdong River Delta, Busan city, South Korea. A detailed description of the geotechnical properties of Busan clay in this area was reported in Chung et al. (2012). The field sampling method based on the pre-borehole technique with the oil-operated fixed-piston sampler (ONS) produced by Chung and Kweon (2013). Steel sampling tubes with an inner diameter of 115 mm and a thickness of 20 mm was initially advanced 0.5 m above the sampling depth. After sampling, the tubes were retrieved by the sampler from the boreholes, both ends of the retrieved tubes were covered with about-20-mm-thick paraffin wax. They were transported to the laboratory and vertically extruded by a sample extruder and then kept in the humidity room.

The nearly middle pieces of each extruded sample were selected to limit the sampling disturbance. They were trimmed into rings, which were then inundated in de-aired and distilled water for 1-day saturation prior to consolidation tests. The incremental loading (IL_{24}) one-dimensional consolidation tests according to Standard ASTM D2435 (1996) were conducted with a load increment of 1.0 and in 24 hours for each loading step. Research on the saturation and cell effects on IL test results showed that unsaturation and instrument insignificantly affected on compression curve of Busan clay retrieved by ONS (Chung et al. 2014). Hence, it is possible to use Terzaghi's consolidation theory for fully-saturated clay to obtain true c_v from IL_{24} test, which is primarily adopted in the revised methods.

Table 1. Summary of methods for interpretation of consolidation coefficient using oedometer tests.

Method	Procedure basis	References
Time-displacement (Group 1)	Time t_{100} is the intersection of extension of steepest linear portion and extension of final linear part in the plot of deformation versus log time.	Casagrande and Fadum (1940)
	Time t_{90} is the intersection of 1.15 times initial linear portion and latter portion of the curve in the plot of deformation versus root square of time.	Taylor (1948)
	Time $t_{22.14}$ is the intersection of extension of steepest linear portion and deformation line at t=0 in the plot of deformation versus log time.	Robinson and Allam (1996)
	Time t_{70} is the infection point of further extension of steepest linear portion from the curve in the plot of deformation versus log time.	Mesri et al. (1999)
	Time t_{60} is the point where the initial linear part deviates from the curve in the plot of deformation versus root square of time.	Feng and Lee (2001)
	Non-graphical construction of coefficient of consolidation is built from a consolidation formula of Hansen (Hispa 2003).	Chan (2003)
	The deformation at t_{100} is the intersection of 45^0 line and deformation line which is determined from 2 points after initial linear portion in the curve of displacement versus root square of time.	Al-Zoubi (2015)
Time-velocity (Group 2)	Time t_{100} is determined at T=1 through two diagnostic curve methods which are proposed by comparing the scatter plots of velocity and time x velocity versus time with the theoretical consolidation curve.	Singh (2007)
Velocity-displacement (Group 3)	Each c_v value is determined from the linear portions in the plots of velocity and inverse velocity versus displacement. These two c_v with others from Taylor's (1948) method and its modified value are averaged to obtain the final c_v.	Mckinley and Sivakumar (2009)
	Time t_{100} is the steepest slope of the curve in plot of displacement versus logarithm of velocity.	Tewatia et al. (1998, 2012)

3 TESTING RESULTS AND DISCUSSION

Fig. 1 shows the c_v-σ'_v curves from samples that were taken from the borehole D2-O2 and then tested in National Research Laboratory (NRL), Busan city, Korea. A total of 11 curves of consolidation coefficient changing with effective stress were plotted and measured by different methods in this figure. A sample at the upper layer of Tidal Flat (TF) was selected with a representative at the depth of 4.83 m.

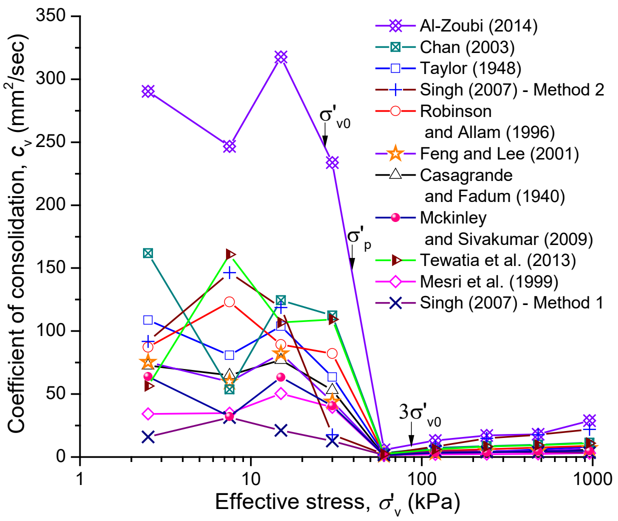

Fig. 1. c_v curves for the upper Tidal-Flat layer (D2-O2-4.83 m).

As can be seen in Fig. 1, the vertical coefficient of consolidation c_v fluctuates widely in the stress range smaller than in-situ effective stress σ'_{v0}, regardless of the methods used to determine c_v-values. This is attributed to the fact that early loadings do not produce significant settlements in the over-consolidated (OC) state of soil sample, which causes a minute primary consolidation or even a vague identification of end-of-primary consolidation settlements.

In terms of methods investigated in Fig. 1, the $c_{v(OC)}$ obtained by Al-Zoubi (2014) presents the highest value, around 2.6 mm^2/s, while Mesri et al.'s (1999) and Singh's (2007) methods (method 1) form the lowest level of about 0.25 mm^2/s. This is simply because the c_v from Al-Zoubi's method heavily relies on the slope of initial linear consolidation curve in root-time plot, compared to two latter methods. Overall, all methods used for Busan clay exhibited an erratic behaviour of $c_{v(OC)}$ with the average constant value of 1.2 mm^2/s.

On the other hand, all the c_v-values drop significantly when the effective stress passes the yield value or pre-consolidation stress σ'_p (Fig. 1). This stress divides the Busan clay c_v-curve into three obvious parts: (i) a roughly leveling-off of $c_{v(OC)}$, followed by (ii) a collapse slope around σ'_p and finally (iii) a slight increase of the c_v at normal-consolidated (NC) state of clay, $c_{v(NC)}$. Unlike $c_{v(OC)}$, $c_{v(NC)}$ is approximate among all 10 methods with c_v-values at tresses after σ'_p. This unification can be explained by the effective implementation of all methods at high levels of stress. In NC state, the sample settlements are massive, equivalent to longer primary consolidation so the $c_{v(NC)}$ is extremely low. However, this causes a value duplication and difficultly to compare each curve (Fig. 1). To clarify this tendency of $c_{v(NC)}$, Fig. 2 illustrates $c_{v(NC)}$ from all surveyed methods which were expressed in comparison with that determined by Casagrande and Fadum (1940). Depths of 4, 12, 30m, which were collected as depths at different profile layers (i.e. TF[U], IS and TF[L]) are depicted in Fig. 2a-c, respectively.

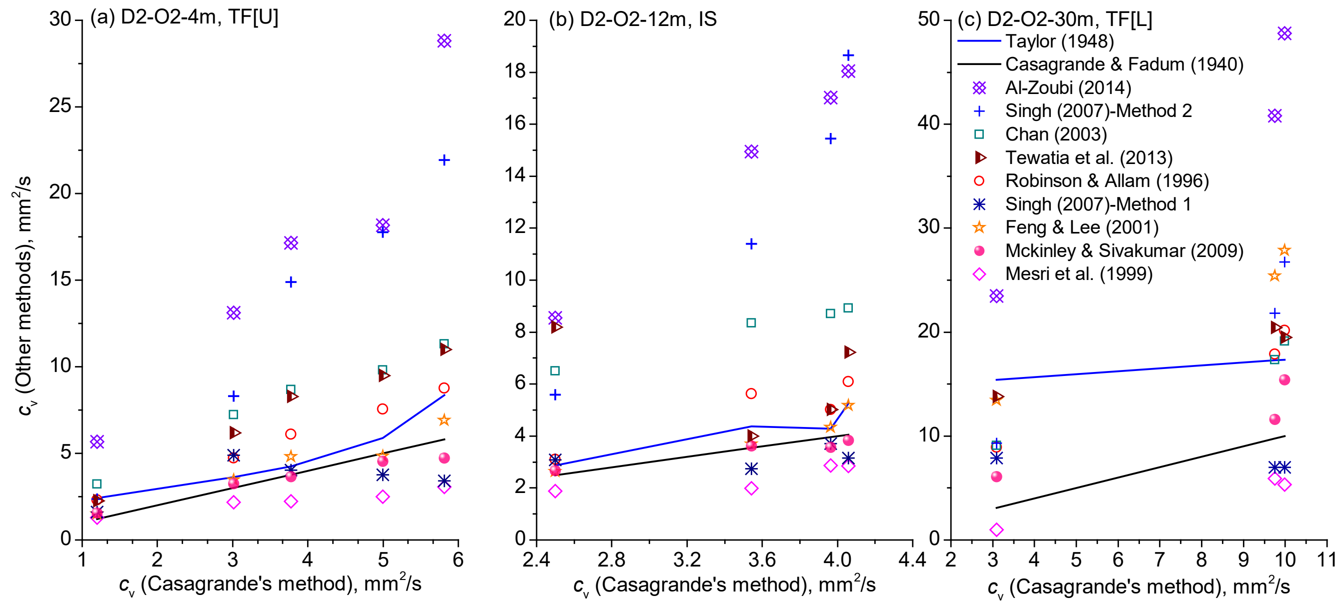

Fig. 2. Comparison of the values of normal-consolidated c_v from different methods with Casagrande and Fadum's (1940) method in 3 different layers of Busan clay profile.

Table 2. Coefficient of consolidation measured by different methods for Busan clay.

Soil layer (m)	In-situ stress, σ'_{vo} (kPa)	c_v (mm²/s) at $3\times\sigma'_{v0}$ from 3 groups of method										
		Group 1(time-displacement)							Group 2 (time-velocity)		Group 3 (velocity-displacement)	
		Casagrande & Fadum (1940)	Taylor (1948)	Robinson & Allam (1996)	Mersi et al. (1999)	Feng & Lee (2001)	Chan (2003)	Al-Zoubi (2014)	Singh (2007) -Med 1	Singh (2007)-Med 2	Mckinley & Sivakumar (2009)	Tewatia et al. (2012)
TF[U] (4.83)	28.98	2.01	2.95	3.41	1.68	2.39	5.02	9.01	3.08	5.02	2.33	4.01
IS (12.43)	68.13	3.23	3.93	4.87	1.96	3.38	7.80	13.05	2.84	9.68	3.33	5.24
TF[L] (30.48)	178.54	1.29	17.73	19.96	7.04	28.16	19.25	44.85	6.77	24.72	12.87	21.94

Referring to Fig. 2, c_v determined based on Taylor's (1948) method is constantly higher than c_v determined by the log-time method (Casagrande and Fadum 1940). The discrepancy between these two c_v-values was wider when the sample belongs to TF[L] (Fig. 2c) while the difference was insignificant for the clay samples in TF[U] and IS layer (Fig. 2a-b). The explanation for this lies on the initial void ratio e_0 and low disturbance level of samples. Consequently, the initial compression has a major impact on shorter primary consolidation in TF[L] samples than those in TF[U] and IS; hence, the methods depending on this early compression (e.g. Taylor's (1948) method) produces significantly high values of c_v, compared to other methods based on σ'_p (e.g. the log-time method) (Fig. 2c).

As can be seen in Fig. 2, the value of c_v from Al-Zoubi et al.'s (2014) and Singh's (2007) method 2 are extremely high, especially $c_{v(NC)}$ by Al-Zoubi et al. (2014), which outnumbers those by Taylor (1948) and Casagrande and Fadum (1940) about 5 to 1, making these two $c_{v(NC)}$ curves outstanding from others (Fig. 1). Tewatia et al.'s (1998) and Chan's (2003) methods produce the second highest value of c_v, followed by c_v from the Robison and Allam's (1996) method which is just above the Taylor's (1948) value. This is due to the fact that Robinson and Allam calculate c_v from U=22.11% which is against to c_v from U=90% after Taylor (1948). Perfectly, two methods from Feng and Lee (2001) and McKinley and Sivakumar (2009) generate c_v in the range of root- and log-time c_v values. However, Feng and Lee's (2001) values are out of this range for deeper sample in TF[L] layer (Fig. 2c). This is entirely understandable since the initial compression markedly influences on the soil at the depth of 30 m. Therefore, the McKinley and Sivakumar's (1940) method is recommended for c_v in all soil profiles of Busan clay.

To compare the methods in terms of group, Table 2 summarized the $c_{v(NC)}$ values determined from the three depths based on different methods. The c_v in the normally consolidated soil state is regarded as the c_v-value at the stress that equates to $3\times\sigma'_{v0}$. This is to guarantee the c_v-value lying on the NC-c_v curve. All values of consolidation coefficient are shown in Table 2, compared with the increase of overburden stress σ'_{v0} at three soil stratum units.

It can clearly be observed from Table 2 that c_v-values are larger with an increase in the in-situ stress, except the Singh's method 1. Al-Zoubi's method gives the highest values while Mersi et al.'s method stands for the lowest ones. Furthermore, no similarity of c_v-value is observed in each group, and the discrepancy is widened approximately twofold. However, the obvious parallel of c_v can be drawn between different groups, namely Casagrande and Fadum's method in Group 1 and Mckinley and Sivakumar's method in Group 3. Group 2 suffers the low values from Singh's method 1, equal to values from Mesri et al. (1999), but also high c_v-value from the Singh's method 2 which approximates to the values from Al-Zoubi's and Tewatia's method. By and large, the Mckinley and Sivakumar's method is suggested for determining the c_v of Busan clay as it produces the reasonable values in the average range of all considered methods.

For future studies, although IL_{24} test can give the c_v-value in a reasonable range, its accuracy might be affected by water sucking air in testing room during long testing duration, the secondary compression process and limited reading data. The constant rate of strain (CRS) and the end-of-primary incremental loading (IL_{EOP}) test, therefore, would be recommended to further improve the precision of consolidation coefficient of Busan clay.

4 CONCLUSIONS

The following conclusions can be drawn from the findings of this study:

Ten methods to determine the coefficient of consolidation c_v were reviewed. They could be classified into three groups including time-displacement, time-velocity and velocity-displacement.

Consolidation data from Nakdong River Delta site were analyzed. The outcomes from consolidation test of samples at three depths of each soil stratum, upper Tidal Flat, Inner Shelf and lower Tidal Flat.

Al-Zoubi's (2014) method tends to give significantly high value of c_v, while the Mersi et al.'s (1999) method underestimated the c_v-value. These time-displacement methods produce a wide range of c_v while the time-velocity method 1 and 2 by Singh (2007) have a large discrepancy in their own c_v-values.

The velocity-displacement method, proposed by McKinley and Sivakumar (2009), yield reasonable values compared to the methods by Casagrande and Fadum (1940) and Taylor (1948), suggesting the method can be a proper alternative to determine the consolidation coefficient of Busan clay profile.

Constant-rate-of-strain and end-of-primary incremental loading consolidation tests are suggested for future research on the consolidation coefficient of clay, obtained by the oil-operated fixed-piston sampler.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) NRL Program grant funded by the Korea government (MEST), National Research Laboratory in Dong-A University, S. Korea; University of Technology and Education, the University of Danang, Vietnam; University of Technology Sydney, Australia and other researchers at these universities providing valuable assistance.

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