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Laboratory determination of coefficient of consolidation from pore water pressure measurement

Abstract

ICE Publishing: all rights reserved. In the recent past, many studies have been carried out on the determination of coefficient of consolidation (c_v) from the time (t)-deformation (d) data obtained from conventional consolidation tests. Several researchers have also proposed different curve fitting procedures for determining c_v from the t - d data. It is anticipated that the c_v values obtained from the t - d data may be influenced by initial and secondary compressions. Nevertheless, the pore water pressure data measured during the consolidation process will be independent of initial and secondary compressions. In this study, the conventional Asaoka (1978) method is extended to evaluate c_v and end-of-primary (EOP) consolidation from the pore water pressure data measured from laboratory experiments. Laboratory experiments were carried out on the modified one-dimensional consolidation apparatus on different remoulded clay samples measuring pore water pressure during the consolidation process. The c_v and EOP computed from the proposed approach have been compared with the results of the t - d data and found to be in good agreement.

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Laboratory determination of coefficient of consolidation from pore water pressure measurement

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In the recent past, many studies have been carried out on the determination of coefficient of consolidation (c_v) from the time (t)–deformation (d) data obtained from conventional consolidation tests. Several researchers have also proposed different curve fitting procedures for determining c_v from the t – d data. It is anticipated that the c_v values obtained from the t – d data may be influenced by initial and secondary compressions. Nevertheless, the pore water pressure data measured during the consolidation process will be independent of initial and secondary compressions. In this study, the conventional Asaoka (1978) method is extended to evaluate c_v and end-of-primary (EOP) consolidation from the pore water pressure data measured from laboratory experiments. Laboratory experiments were carried out on the modified one-dimensional consolidation apparatus on different remoulded clay samples measuring pore water pressure during the consolidation process. The c_v and EOP computed from the proposed approach have been compared with the results of the t – d data and found to be in good agreement.

KEYWORDS: clays; consolidation; deformation

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NOTATION

c_v	coefficient of consolidation
d	deformation
d_{100}	deformation at EOP
H	drainage path
s_j	settlement at time j
s_{j+1}	settlement at any time $j + 1$
T	time factor
t	time
U_z	degree of consolidation
u	pore water pressure
u_0	initial pore water pressure
u_{100}	pore water pressure at end of primary
u_j	pore water pressure at any time j
u_{j+1}	pore water pressure at any time $j + 1$

INTRODUCTION

A reasonably good estimate on the coefficient of consolidation (c_v) is required for evaluating the rate of deformation/settlement of a clayey soil due to the overburden pressure. The classical work of Terzaghi's theory of one-dimensional consolidation forms the basis for most of the methods available for the determination of c_v . The coefficient of consolidation is generally estimated from the time–deformation (t – d) data obtained from the one-dimensional consolidation tests. Several research studies have been carried out on the determination of c_v from the t – d data based on the curve fitting procedures (e.g. Casagrande & Fadum, 1940; Parkin, 1978; Sridharan *et al.*, 1987; Robinson & Allam, 1996; Sridharan & Prakash, 1993, 1997, 1998; Taylor, 1948, to name a few). The curve fitting

procedures basically utilise the characteristic features of the theoretical degree of consolidation (U) and time factor (T) relationship with the laboratory t – d data. It is important to note that the c_v determined from the experimental t – d data may be influenced by initial (immediately on the application of load) and secondary compressions (Sridharan *et al.*, 1995). Sridharan *et al.* (1995) highlighted the fact that initial compression increases and secondary compression decreases the value of c_v computed based on the t – d data. However, Tan & Chew (1996) have shown that the rectangular hyperbola method (Sridharan *et al.*, 1987) and the Asaoka (1978) method will give very good predictions for c_v and end of primary (EOP) and is a useful tool in monitoring consolidation in the field. Recently, Prakash *et al.* (2013) highlighted that Asaoka (1978) method is a very simple approach for computing c_v and (EOP) compression from laboratory deformation data. Alternately, Taylor (1948) has shown a reasonable agreement on the pore water pressure measured in the field and laboratory during consolidation. Lot of laboratory experimental studies have been carried out, in the past, on the measurement of pore water pressure during consolidation (e.g. Whitman *et al.*, 1961; Gibson, 1963; Northey & Thomas, 1965; Sonpal & Katti, 1973; Robinson, 1999; Robinson & Soundara, 2008). Most of the studies were carried out by mounting a pore water pressure measurement device at the base of the consolidation apparatus. However, the compliance of the pore pressure measuring device has significant influence on the pore water pressure data obtained from these tests. Moreover, an analysis of the laboratory-measured pore pressure data highlighted that the c_v values obtained from the pore water pressure may differ significantly compared with settlement analysis (Olson, 1986).

Although many methods are available for computing c_v from the t – d data, only very few methods can be found in the literature on the determination of c_v using the pore water pressure data (e.g. Robinson, 1999; Robinson & Soundara, 2008). Robinson (1999) has proposed a graphical procedure for determining c_v from U –compression (δ)– $\sqrt{t}$ curve. A linear relationship observed between pore water pressure and

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compression was adopted for computing c_v . Robinson & Soundara (2008) developed a curve fitting procedure for computing c_v from the degree of dissipation at the base of the sample (U_b) against $\log t$ relationship and highlighted that this method is less influenced by secondary compression. In this study, conventional Asaoka (1978) method has been extended to compute the value of c_v from the pore water pressure data.

THEORETICAL CONSIDERATION

Asaoka (1978) proposed a graphical approach for estimating the value of c_v and EOP compression based on Mikasa's consolidation theory. The mathematical deduction for the method is not very simple (Mesri & Huvaj-Sarihan, 2009); however, the graphical approach is simple and widely used by practising engineers. The procedure consists of plotting settlement/deformation data taken at regular intervals against the elapsed time. More details on the procedure for evaluating c_v based on the settlement data can be found elsewhere (e.g. Asaoka, 1978; Tan & Chew, 1996; Mesri & Huvaj-Sarihan, 2009; Prakash *et al.*, 2013). Recently, Mesri & Huvaj-Sarihan (2009) proposed a simple mathematical deduction for Asaoka's (1978) method for the settlement data obtained from one-dimensional consolidation test. This mathematical deduction has been extended, in this study, to consider the pore water pressure measured at the base of the sample.

The relationship between the degree of consolidation and pore water pressure at a distance z at any time t is given by

$$U_z = \frac{u_0 - u_j}{u_0} \quad (1)$$

where U_z is the average degree of consolidation; u_0 is the initial pore water pressure and u_j is the pore water pressure at any time j .

The relationship between the degree of consolidation (U_z) against time (t) proposed by Terzaghi for linear distribution of initial excess pore water pressure for $U_z > 50\%$ can be expressed as

$$U_z = 1 - \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 c_v t}{4H^2}\right) \quad (2)$$

and

$$T = \frac{c_v t}{H^2}$$

where T is the time factor, c_v the coefficient of consolidation and H is the drainage path.

Substituting equation (1) into equation (2)

$$\frac{u_0 - u_j}{u_0} = 1 - \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 c_v t}{4H^2}\right) \quad (3)$$

Equation (3) can be rewritten as

$$\frac{u_j}{u_0} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 c_v t}{4H^2}\right) \quad (4)$$

Consider settlements at elapsed time t_j and t_{j+1} and let $A = -\pi^2 c_v / 4H^2$, then

$$\frac{u_j}{u_0} = \frac{8}{\pi^2} \exp(A t_j) \quad (5)$$

and

$$\frac{u_{j+1}}{u_0} = \frac{8}{\pi^2} \exp(A t_{j+1}) \quad (6)$$

Dividing equation (6) by equation (5), one can get

$$\frac{u_{j+1}}{u_j} = \exp[A(t_{j+1} - t_j)] \quad (7)$$

Let $t_{j+1} - t_j = \Delta t$ constant and $A' = \exp(A \Delta t)$

$$u_{j+1} = u_j A' \quad (8)$$

It is evident from equation (8) that a plot of u_{j+1} against u_j should be a straight line having a slope A' and when $u_{j+1} = u_j$ this will intersect the origin making a 45° line.

Assuming λ to be the slope of u_{j+1} against u_j , equation (7) becomes

$$\ln(\lambda) = A \Delta t \quad (9)$$

Expanding equation (9) by substituting for A

$$c_v = \frac{-4H^2 \ln \lambda}{\pi^2 \Delta t} \quad (10)$$

It is to be noted that equation (10) is very similar to the equation proposed by Asaoka (1978) for settlement data. However, the pore water pressure data should be selected for $U_z > 50\%$ for computing c_v for the case of one-dimensional consolidation.

CONSOLIDATION TESTING PROGRAMME

Laboratory experiments were carried out using the modified one-dimensional consolidation apparatus to capture the dissipation of pore water pressure during consolidation. A miniature sensitive pore pressure sensor was attached to the base of the sample to measure the excess pore water pressure during the consolidation process. Studies have reported that pore water pressure data are significantly influenced by the stiffness of the pore water pressure sensors (e.g. Perlof *et al.*, 1965; Robinson, 1999). Therefore, proper care was taken in selecting the pore pressure sensors to avoid any compliance of the sensors on the pore water pressure data. Figure 1 shows the experimental set-up used for the current investigation. The soil samples used in this study are collected from the suburbs of University of Wollongong and identified as

Fig. 1. Experimental test set-up

Table 1. Comparison of c_v based on different methods

Soil type	Specific gravity, G	Liquid limit: %	Plastic limit: %	Pressure increment: kPa	Proposed Asaoka (1978) method using pore water pressure data $c_v (\times 10^{-6} \text{ m}^2/\text{s})$	Conventional Asaoka (1978) method using deformation data $c_v (\times 10^{-6} \text{ m}^2/\text{s})$	Log t method using deformation data (Casagrande's conventional method) $c_v (\times 10^{-6} \text{ m}^2/\text{s})$
Clay 1 (Albion park clay)	2.64	59.5	38.5	0–20 20–40 40–80	0.03 0.06 0.10	0.02 0.03 0.04	0.02 0.05 0.05
Clay 2 (kaolinite)	2.62	56.2	26.4	20–40	0.10	0.05	0.07
Clay 3 (Picton clay)	2.62	57.0	—	80–160	0.06	0.02	0.06

Fig. 2. Typical experimental variation of pore water pressure with time **Fig. 3.** Typical experimental variation of deformation with time (1 div = 0.002 mm)

clay 1 (Albion park clay), clay 2 (kaolinite) and clay 3 (Picton clay). The properties such as specific gravity, liquid limit and plastic limit of the soil samples are tabulated in Table 1. The sensitive pore pressure sensor (100 mV output, 0.25% accuracy and 0.5 ms response time) is attached to the base of the sample and can measure a very quick response of pore pressure data. The pore pressure sensor was connected to a data acquisition system and was able to capture the data immediately on the application of load; hence, minimising the compliance effect. The soil samples were prepared in the consolidation ring having a dimension of 60 mm dia. and 20 mm height. The silicon grease was applied on the sides of the wall of the consolidation ring to minimise friction. The soil was mixed with a predetermined amount of water (1.15 times liquid limit water content) and placed in the consolidation ring. A porous stone and top cap were then placed on the soil sample and loading was carried out by keeping a load increment ratio of one. The deformation and excess pore water pressure corresponding to time were measured simultaneously during the consolidation testing. Figures 2 and 3 show the typical plot of pore water pressure and deformation with $\log t$ for clay 1, respectively. The initial response of the pore water pressure measuring system indicated that the response of the pore water pressure (u) measured and the applied pressure (σ_n) resulted in $u/\sigma_n \sim 1$. This further shows the potential of the modified apparatus in capturing pore pressure dissipation during the consolidation stage. It is evident from Fig. 2 that the initial excess pore water pressure developed during the load increment decreases with time. As expected the deformation

Fig. 4. Plot of s_{j+1} against s_j

Fig. 5. Plot of u_{j+1} against u_j

also increases with decrease in the pore water pressure (Fig. 3). Figure 4 shows the plot of s_{j+1} against s_j for clay 1 (Albion park clay) for a pressure increment of 0–20 kPa. The conventional Asaoka (1978) method is used to calculate the values of c_v (e.g. Mesri & Huvaj-Sarihan, 2009; Prakash *et al.*, 2013) for $\Delta t = 500$ s. The intersection of 45° line from the origin with the settlement data will give a reading corresponding to EOP consolidation. Figure 5 presents the plot of u_{j+1} against u_j for clay 1 for a pressure increment of 0–20 kPa. The slope of the line λ obtained from Fig. 5 can be used to compute c_v using equation (10) for $\Delta t = 500$ s. The intersection of a 45° line from the origin with the pore pressure data will give the pore pressure value at the EOP consolidation point. The deformation reading corresponding to this pore water pressure value will give the deformation at the EOP consolidation (d_{100}).

DISCUSSIONS

Table 1 shows some typical results of c_v computed from the pore pressure data using modified Asaoka (1978) method along with the conventional log t method proposed by Casagrande & Fadum (1940) and that by Asaoka (1978). It is evident that the c_v values computed based on the pore water pressure data are slightly higher than the values computed from log t and Asaoka (1978) method using the deformation data. The lower value of c_v observed from the deformation analysis is mainly due to the influence of secondary compression (e.g. Sridharan *et al.*, 1995) during consolidation. However, the values of c_v from the deformation data using conventional Asaoka (1978) method show

Fig. 6. Comparison of d_{100} obtained from the proposed method with those obtained from the conventional Asaoka (1978) and log t methods

a close relationship with the conventional log t method, which is in agreement with the results reported by Prakash *et al.* (2013). Figure 6 shows the variation of sample thickness corresponding to d_{100} (EOP) computed from the proposed method compared with the Asaoka (1978) and log t methods. Even though there is a marked difference in the c_v values from pore pressure data and deformation data, there is practically no difference in the EOP values computed from these methods (Fig. 6). It is important to note that Mikasa's theory follows a different law for excess pore water pressure compared with the classical Terzaghi's theory. However, the void ratio–pressure relationship can be taken as linear for any pressure increment applied in the tests. The determination of c_v carried out for particular load increments will not significantly influence the results. Moreover, Asaoka's (1978) method overestimates the values of c_v for $U_z < 50\%$ for the case of one-dimensional consolidation. On the contrary, Asaoka's (1978) method is applicable to the entire time interval ($U_z = 0$ –100%) for radial consolidation.

RECOMMENDED PROCEDURE

- Select a series of $u_1, u_2, u_3, \dots, u_j, u_{j+1}, \dots$ corresponding to times $t_1, t_2, t_3, \dots, t_j, t_{j+1}, \dots$ such that $t_{j+1} - t_j$ is a constant for $U > 50\%$.
- Plot u_{j+1} against u_j such as to obtain a straight line.
- The slope of the straight line (λ) can be used to compute the value of c_v using equation (10).
- Draw a 45° line through the origin to intersect the u_{j+1} against u_j line. The point of intersection will give the pore water pressure at the end of primary consolidation (u_{100}).
- The u_{100} obtained in the earlier step can be compared with the corresponding deformation values to obtain the deformation at the EOP consolidation (d_{100}).

CONCLUSIONS

In this paper, an extended Asaoka (1978) method has been presented on the determination of coefficient of consolidation and EOP consolidation from pore water pressure data. A simple algebraic deduction was carried out for developing a graphical procedure to evaluate c_v from the pore water pressure data. Laboratory experiments were also carried out on a modified consolidation apparatus capturing the pore pressure data using a very sensitive pore pressure sensor. The deformation and pore pressure data were recorded simultaneously using a dial gauge and data acquisition system,

respectively. The c_v values obtained from the pore water pressure analysis using the modified Asaoka (1978) method will predict more realistic values compared with deformation data analysis as the latter is influenced by initial and secondary compressions. However, the EOP computed from pore water pressure and deformation data shows very close agreement.

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