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<thead>
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<th>New observational method for prediction of one-dimensional consolidation settlement</th>
</tr>
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<tr>
<td>Author(s)</td>
<td>Guo, Wei; Chu, Jian</td>
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<td>Date</td>
<td>2017</td>
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</tbody>
</table>
New observational method for prediction of one-dimensional consolidation settlement

W. GUO* and J. CHU*

The Chapman–Richards model is adopted in this paper to best fit the Terzaghi’s one-dimensional consolidation curve. The obtained formula fits the theoretical solution well, with a regression coefficient $R^2$ of 0.9995 and an error of less than 2%. By adopting this model, a new method to predict the ultimate settlement and the coefficient of consolidation using monitoring settlement data is proposed. The accuracy of the proposed method is verified against oedometer test and field monitoring data. For the cases verified, the ultimate settlement predictions from the proposed method are more reliable than those from the Asaoka’s method for the different range of settlement data.

KEYWORDS: consolidation; ground improvement; monitoring

INTRODUCTION

Average degree of consolidation has been commonly used as a design specification for soil improvement using preloading (Hansbo, 1981; Holtz, 1987). Normally the average degree of consolidation is determined as the ratio of settlement at a given time over ultimate consolidation settlement. The settlement at a given time is measured and the ultimate consolidation settlement is predicted. As the soil properties are highly variable in the field, it is difficult to predict reliably the ultimate consolidation settlement using the $e$–log $\delta_t$ as determined from one-dimensional oedometer tests (Holtz, 1987; Chung, 1999; Arulrajah et al., 2003, 2004; Bo et al., 2003; Chng et al., 2014). Thus, in practice, the observational method is usually adopted to use the field monitoring data to predict the ultimate settlement. Two such methods are Asaoka (1978) and hyperbolic methods (Tan et al., 1991; Tan, 1995; Tan & Chew, 1996; Chng et al., 2009, 2014). Sometimes, the overall coefficient of consolidation is also determined from these methods.

The Asaoka’s method was derived from Terzaghi’s one-dimensional theory (Terzaghi et al., 1996) in which the settlement plotted against time, $\delta$, relationship can be written as

$$\delta = \delta_{ult} \left[ 1 - \exp \left( -\frac{12}{5} \cdot \frac{c_v}{H^2} \cdot t \right) \right] \quad (1)$$

where $\delta$ and $\delta_{ult}$ are the ground settlement at a given time $t$ and the ultimate ground settlement, respectively; $c_v$ is the coefficient of vertical consolidation; and $H$ is the drainage path.

From equation (1), the degree of consolidation in the vertical direction $U_v$, as calculated as $\delta/\delta_{ult}$ can be given as

$$U_v = 1 - \exp \left( -\frac{12}{5} \cdot \frac{c_v}{T_v} \right) \quad (2)$$

where $T_v = c_v/\Delta H^2$ is the time factor.

When a series of settlements at different time intervals $\delta_1, \delta_2, \ldots, \delta_n$ are selected from the monitoring data in such a way that $\delta_n$ is the settlement at time $t_n$ and the sampling interval $\Delta t = t_n - t_{n-1}$ is a constant, the relationships between settlement $\delta_n$ and $\delta_{ult}$ can be expressed as

$$\delta_{n+1} = \beta_0 + \beta_1 \delta_n \quad (3)$$

where $\beta_0$ is the intercept and $\beta_1$ is the slope of the straight line in the $\delta$ against $\delta_{ult}$ plot.

At the end of the primary consolidation, $\delta_n = \delta_{ult}$ and thus $\delta_{ult}$ can be calculated as

$$\delta_{ult} = \frac{\beta_0}{1 - \beta_1} \quad (4)$$

The coefficient of consolidation, $c_v$, can be estimated using (Balasubramaniam & Brenner, 1981)

$$c_v = - \frac{5}{12} \cdot \frac{H^2 \ln \beta_1}{\Delta} \quad (5)$$

Equations (1)–(5) form the basis of Asaoka’s method, which has often been used to predict ultimate settlement and coefficient of consolidation. However, this method underestimates the ultimate settlement and overestimates the coefficient of consolidation depending on the chosen sampling period (Asaoka, 1978; Edil et al., 1991; Arulrajah et al., 2003). This can be seen from the comparison in Fig. 1(b) where the difference between equation (1) and the Terzaghi’s consolidation curve is relatively large and only becomes less than 6% when $U_v > 80\%$ or $T_v > 0.55$. It should be stated that the curves shown in Fig. 1 are only for the case with uniform loading pressure and one-dimensional consolidation with either one-way or two-way drainage.

As there is no closed form equation, the $U_v$ plotted against $T_v$ relationship in Terzaghi’s one-dimensional consolidation theory has been written into two simplified equations depending on whether $U_v$ is greater than 0.53 (Taylor, 1942; Leonards, 1962). As this is not convenient in engineering practice and cannot provide unique values of the factors relevant to consolidation, other single approximate equations have also been proposed. One of them is proposed by Chng et al. (2014) as follows

$$T_v = -0.39 \ln \left( \frac{1 - U_v^{0.002}}{0.8283} \right) \quad (6)$$

or

$$U_v = \left[ 1 - 0.8283 \exp(-2.564 T_v) \right]^{0.99} \quad (7)$$
NEW OBSERVATIONAL METHOD TO PREDICT 1D CONSOLIDATION SETTLEMENT

PROPOSED OBSERVATIONAL METHOD

As the settlement, δ, plotted against time, t, behaviour of a clay layer follows a uniform relationship with respect to δult, c_v and H in one-dimensional consolidation, equation (10) is further processed to be used as an observational model to predict δult, c_v using monitored settlement data. Using the same procedure as in Asaoka’s method, such as selecting settlement δ_1, δ_2, ... δ_n at the constant sampling period Δt=t_n−t_{n−1} from the settlement curve, gives the expressions of settlement δ_n, δ_{n−1} and their corresponding time t_n, t_{n−1} as shown in equations (11) and (12), respectively.

$$δ_n = δ_{ult} \left[1 - \exp\left(-\frac{2c_v}{H^2} t_n\right)\right]^{0.6}$$  

Combining equations (11) and (12) gives the relationship between the settlements δ_n and δ_{n−1} as

$$δ_n^{1.667} = α + βδ_{n−1}^{1.667}$$  

$$α = (1 - β)δ_{ult}^{1.667}$$  

$$β = \exp\left(-\frac{2c_v}{H^2} Δt\right)$$

Equation (13) shows that the δ_n^{1.667} against δ_{n−1}^{1.667} plot is a straight line with slope α and intercept β. The procedure is similar to Asaoka’s method except in using δ_n^{1.667} for the graph. From equation (14) the ultimate settlement δ_{ult} can be derived as

$$δ_{ult} = \left(\frac{α}{1 - β}\right)^{0.6}$$

Using equation (15), the coefficient of consolidation c_v can be derived as

$$c_v = -\frac{H^2 \ln β}{2Δt}$$

VERIFICATION USING OEDOMETER TESTING DATA

Effect of data range used for prediction

To investigate the influence of data range on the accuracy of the proposed method, Terzaghi’s U_v−T_v solution is adopted with predefined parameters c_0 = 1, H = 1, δ_{ult} = 1 and the range of settlement data from U_0 to U_{30}, U_0 to U_{60} and U_0 to U_{90}.

The proposed method as in equations (16) and (17) is used to predict δ_{ult} and c_v, and the results are shown in Table 1. The value of δ_{ult} and c_v predicted using the settlement data in
the range from $U_0$ to $U_{30}$ and sampling period $\Delta T = 0.025$ is underestimated by 47.4% and overestimated by 253%, respectively. When the data in the range from $U_0$ to $U_{60}$ are used, $\delta_{\text{uni}}$ is underestimated by 6.7% and $c_v$ is overestimated by 13.1%, which is acceptable for common engineering application. When the settlement data in the range from $U_0$ to $U_{90}$ are used, the errors are further reduced to 4% overestimation for $\delta_{\text{uni}}$ and 9.4% underestimation for $c_v$.

For comparison, Asaoka’s method as in equations (4) and (5) is also adopted to predict $\delta_{\text{uni}}$ and $c_v$. The percentages of error between this method and the theoretical values are also computed. The results are given in Table 1. Using the early settlement data from $U_0$ to $U_{30}$ and sampling period $\Delta T = 0.025$, Asaoka’s method underestimates $\delta_{\text{uni}}$ by 65.1% and overestimates $c_v$ by 1060.3%. Using the settlement data from $U_0$ to $U_{60}$, $\delta_{\text{uni}}$ is underestimated by 40.3% and $c_v$ is overestimated by 335.8%, which are still not acceptable. Even when settlement data from $U_0$ to $U_{90}$ are used, $\delta_{\text{uni}}$ is still underestimated by 13% and $c_v$ is overestimated by 104.7%. Compared with Asaoka’s method, the proposed method is much improved in terms of accuracy in prediction as well as the data range required (up to 60% in the proposed method) to make a reasonable prediction. 

**Effect of sampling period**

Some previous studies indicated that the accuracy of Asaoka’s method is affected by the choice of sampling period $\Delta t$ (Edil et al., 1991; Long et al., 2013). To evaluate the influence of sampling period on the accuracy of prediction, Edil et al. (1991) proposed a parameter $j_{\text{BS}}$ to define the number of samples to reach a 95% degree of consolidation. The suggested sampling period should give a $j_{\text{BS}}$ value between 10 and 30. Similarly, Tan & Chew (1996) used $j_{90}$ to define the number of time increments to give a 90% degree of consolidation, which is shown as

$$j_{90} = \frac{\ln(1 - U_{90})}{\ln \beta}$$

(18)

In this paper, a similar parameter $N_{90}$ is adopted, which is defined as the number of samples to achieve a 90% degree of consolidation

$$c_v N_{90} \Delta t = \frac{H^2}{T_{90}}$$

(19)

Combining equations (15) and (19) and $T_{90} = 0.848$ gives the expression of $N_{90}$ as

$$N_{90} = -\frac{1.696}{\ln \beta}$$

(20)

Terzaghi’s theoretical $U_v - T_v$ curve is adopted to investigate the effect of sampling period $\Delta T$ on the predictions of the proposed method as well as Asaoka’s method. The $\Delta T$ values used in the calculations are 0.005, 0.01 and 0.025 as reported in Table 1. It appears that the selection of $\Delta T$ does not have much of an effect on the $c_v$ and $\delta_{\text{uni}}$ values obtained from the proposed method. When using the settlement data from $U_0$ to $U_{50}$, the proposed method underestimates $c_v$ by about 9% and overestimates $\delta_{\text{uni}}$ by about 4% for all of the three $\Delta T$ values of 0.005, 0.01 and 0.025. A laboratory oedometer test at loading step of 2–4 kPa, as reported by Tan & Chew (1996) was used to evaluate the proposed method and the effect of $\Delta t$ on the prediction. The tested soil was kaolin and the size of the specimen was 75 mm in diameter and 25 mm high. Drainage was permitted only at the top. The coefficient of consolidation $c_v$ was calculated as 0.613 mm/s based on Taylor’s $t_{50}$, and as 0.513 mm/s based on Casagrande’s $t_{50}$. The settlement data were taken from Tan & Chew (1996) with $\delta_{\text{uni}} = 1$ mm. Analyses using six different sampling periods of $\Delta t = 10$, 30, 50, 100, 200 and 300 s were carried out. The plots obtained using the proposed method are shown in Fig. 2(a). The obtained $\alpha$, $\beta$, $R^2$ and computed $c_v$, $\delta_{\text{uni}}$, $N_{90}$ are reported in Table 2. It can be seen that the computed $c_v$, $\delta_{\text{uni}}$ are stable, although the magnitudes of $\alpha$, $\beta$ and $R^2$ are different for different $\Delta t$. The calculated coefficients of consolidation, $c_v$, are 12.3% to 17.8% lower than those from Taylor’s $t_{50}$, or $-1.7\%$ to 4.8% different than those from $c_v$ using Casagrande’s $t_{50}$. For $\Delta t$ ranging from 10 to 300 s, the estimated $\delta_{\text{uni}}$ are approximately the same as those measured with overestimates of only 0.5–1.0%. The $N_{90}$ does not have any obvious effect on the accuracy of the computed $c_v$. 

**Table 1. Effect of sampling period and range of settlement data on the predictions of the proposed and Asaoka’s method (for $c_v = 1$, $h = 1$ and $\delta_{\text{uni}} = 1$)**

<table>
<thead>
<tr>
<th>Proposed method</th>
<th>$\beta_0$</th>
<th>$\beta_0$</th>
<th>$R^2$</th>
<th>$j_{90}$</th>
<th>$c_v$</th>
<th>Error: %</th>
<th>$\delta_{\text{uni}}$</th>
<th>Error: %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T = 0.005$</td>
<td>$U_0 - U_{30}$</td>
<td>0.9592</td>
<td>0.0123</td>
<td>0.9995</td>
<td>41</td>
<td>4.166</td>
<td>316.6</td>
<td>0.487</td>
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<td></td>
<td>$U_0 - U_{60}$</td>
<td>0.9889</td>
<td>0.0100</td>
<td>1.0000</td>
<td>152</td>
<td>1.116</td>
<td>11.6</td>
<td>0.939</td>
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<tr>
<td></td>
<td>$U_0 - U_{90}$</td>
<td>0.9910</td>
<td>0.0097</td>
<td>1.0000</td>
<td>187</td>
<td>0.907</td>
<td>-9.3</td>
<td>1.041</td>
</tr>
<tr>
<td>$\Delta T = 0.01$</td>
<td>$U_0 - U_{30}$</td>
<td>0.9216</td>
<td>0.0240</td>
<td>0.9986</td>
<td>21</td>
<td>4.082</td>
<td>308.2</td>
<td>0.492</td>
</tr>
<tr>
<td></td>
<td>$U_0 - U_{60}$</td>
<td>0.9777</td>
<td>0.0199</td>
<td>0.998</td>
<td>75</td>
<td>1.128</td>
<td>12.8</td>
<td>0.934</td>
</tr>
<tr>
<td></td>
<td>$U_0 - U_{90}$</td>
<td>0.9820</td>
<td>0.0192</td>
<td>1.0000</td>
<td>94</td>
<td>0.908</td>
<td>-9.2</td>
<td>1.039</td>
</tr>
<tr>
<td>$\Delta T = 0.025$</td>
<td>$U_0 - U_{30}$</td>
<td>0.8382</td>
<td>0.0555</td>
<td>0.9980</td>
<td>10</td>
<td>3.530</td>
<td>253.0</td>
<td>0.526</td>
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<tr>
<td></td>
<td>$U_0 - U_{60}$</td>
<td>0.9450</td>
<td>0.0490</td>
<td>0.9993</td>
<td>30</td>
<td>1.131</td>
<td>13.1</td>
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<tr>
<td></td>
<td>$U_0 - U_{90}$</td>
<td>0.9557</td>
<td>0.0473</td>
<td>0.9999</td>
<td>38</td>
<td>0.906</td>
<td>-9.4</td>
<td>1.040</td>
</tr>
</tbody>
</table>

Asaoka’s method

| $\Delta T = 0.005$ | $U_0 - U_{30}$ | 0.8122 | 0.0565 | 0.9821 | 11 | 17.334 | 1635.4 | 0.301 | -69.9 |
|                 | $U_0 - U_{60}$ | 0.9472 | 0.0314 | 0.9972 | 42 | 4.520 | 352.0 | 0.595 | -40.5 |
|                 | $U_0 - U_{90}$ | 0.9755 | 0.0213 | 0.9984 | 93 | 2.067 | 106.7 | 0.868 | -13.2 |
| $\Delta T = 0.01$ | $U_0 - U_{30}$ | 0.6848 | 0.0977 | 0.9693 | 6 | 15.776 | 1477.6 | 0.310 | -69.0 |
|                 | $U_0 - U_{60}$ | 0.8964 | 0.0612 | 0.9922 | 21 | 4.557 | 355.7 | 0.591 | -40.9 |
|                 | $U_0 - U_{90}$ | 0.9516 | 0.0421 | 0.9983 | 46 | 2.067 | 106.7 | 0.870 | -13.0 |
| $\Delta T = 0.025$ | $U_0 - U_{30}$ | 0.4985 | 0.1750 | 0.9750 | 3 | 11.603 | 1060.3 | 0.349 | -65.1 |
|                 | $U_0 - U_{60}$ | 0.7699 | 0.1373 | 0.9778 | 9 | 4.358 | 335.8 | 0.597 | -40.3 |
|                 | $U_0 - U_{90}$ | 0.8844 | 0.1006 | 0.9936 | 19 | 2.047 | 104.7 | 0.870 | -13.0 |
Fig. 2. Influence of sampling period on the plots using (a) proposed and (b) Asaoka's method (data from Tan & Chew (1996))

Table 2. Effect of sampling period on the predictions of the proposed and Asaoka's method (for loading step from 2 kPa to 4 kPa, \(c_v = 0.513 \text{ mm}^2/\text{s}\) from Casagrande \(t_{50}\), and \(c_v = 0.613 \text{ mm}^2/\text{s}\) from Taylor's \(t_{50}\), \(H = 25 \text{ mm}\) and observed \(\delta_{ult} = 1 \text{ mm}\), data from Tan & Chew (1996)).

<table>
<thead>
<tr>
<th>Proposed method</th>
<th>(\Delta t: s)</th>
<th>(\beta)</th>
<th>(\alpha)</th>
<th>(R^2)</th>
<th>(N_{90})</th>
<th>(c_v)</th>
<th>Error: % Casagrande</th>
<th>Error: % Taylor</th>
<th>(\delta_{ult})</th>
<th>Error: % Proposed method</th>
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<td>0.0162</td>
<td>1.0000</td>
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<td>-17.8</td>
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<td>0.0480</td>
<td>0.9977</td>
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<td>-17.7</td>
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<table>
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<tr>
<th>Asaoka's method</th>
<th>(\Delta t: s)</th>
<th>(\beta_1)</th>
<th>(\beta_0)</th>
<th>(R^2)</th>
<th>(j_{90})</th>
<th>(c_v)</th>
<th>Error: % Casagrande</th>
<th>Error: % Taylor</th>
<th>(\delta_{ult})</th>
<th>Error: % Asaoka's method</th>
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<td>35.3</td>
<td>13.2</td>
<td>0.992</td>
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and \(\delta_{ult}\). However, the larger the value of \(\Delta t\), the lower the regression coefficient \(R^2\), suggesting the adoption of \(N_{90} > 20\) to achieve a high value of \(R^2\). For comparison, Asaoka's plots using different sampling periods and settlement data are shown in Fig. 2(b) and Table 2. The calculated \(c_v\) are about 15% and 40% larger than that calculated from Taylor's \(t_{50}\) and Casagrande's \(t_{50}\), respectively. The results also show that \(\delta_{ult}\) is always slightly overestimated, by 1-0% in the worst case.

**COMPARISON USING DATA FROM FIELD TESTS**

The proposed method is applied to two well-documented case records and the predictions are compared with those from the Asaoka's method. The first case is the Changi East reclamation project in Singapore, as reported by Choa et al. (2001), Chu et al. (2005) and Bo et al. (2005). A pilot test was conducted on four, 50 m square subzones to investigate the effect of prefabricated vertical drain spacing. One subzone, termed lot X, was used as a control zone with no drain installed. A 10 m high sand fill surcharge was applied on the surface of the site. The loading history and monitored settlement data are shown in Fig. 3. The clay stratum was about 42.5 m deep with a 2 m thick interlayer of sand and many horizontal sand seams (Chu et al., 2009). The laboratory tests indicate the \(c_v\) of the clay ranges from 0.5 to 2-3 m²/year. More details of the site information, location of the field instrumentation and construction procedure can be found elsewhere (Bo et al., 2005; Chu et al., 2009).

Figure 4(a) shows the plots used to predict \(\delta_{ult}\) and \(c_v\) using the proposed method. A sampling period of 20 days was adopted, with the initial settlement data taken as the settlement at \(t_0 = 260\) days (point A in Fig. 3), which was the beginning of the full load. In the determination of \(c_v\), the total clay thickness was taken as 22·0 m (Chu et al., 2009). The coefficient of consolidation \(c_v\) obtained from the proposed method is 6.87 m²/year, which is higher than that from the laboratory oedometer test, as expected. The obtained \(\delta_{ult}\) from the proposed method is 1.977 m. Based on \(U_c = \delta_{ult}\), the \(U_c\) at \(t = 760\) days is calculated as 39%...
using the proposed method, which matches with the $U_v$ calculated using pore water pressure data (Chu et al., 2009). For comparison, the Asaoka’s plot using the same sampling period and settlement data is shown in Fig. 4(b). The coefficients of consolidation $c_v$ and $\delta_{ult}$ obtained from Asaoka’s method are 21.03 m$^2$/year and 1.226 m, respectively. The $U_v$ at $t = 760$ days from Asaoka’s method is 62.8%. For the presented case history with low degree of

![Fig. 3. Loading history and monitored settlement data at lot X for the Changi East land reclamation project (modified after Chu et al. (2009); mCD = m above chart datum)](image)

![Fig. 4. Plots to predict $c_v$ and $\delta_{ult}$ using (a) proposed and (b) Asaoka’s method)](image)

![Fig. 5. Loading history and monitored settlement data for the embankment constructed on a typical sabkha formation (after Dhowian et al., 1987)](image)
new observational method to predict 1d consolidation settlement

consolidation, the proposed method gives better results than Asaoka’s method.

The second field site is from the town of Jazan situated on the southeast coast of the Kingdom of Saudi Arabia. The soil profile at the site comprised 0–7.2 m thick sabkha crust (mixture of fine sand and silt), 6.0–16.5 m thick compressible sabkha complex (varies from non-plastic fine sand to highly plastic organic clays) and sabkha base (Dhowian et al., 1987). The loading history and monitored settlement are shown in Fig. 5. Based on the settlement data, \(c_v\) of 1.86 m²/day was back-calculated by assuming the sabkha was 9.5 m thick with double drainage (Dhowian et al., 1987). The monitored settlement data shown in Fig. 5 are used to plot Figs 6(a) and 6(b) employing the proposed method and Asaoka’s method, respectively. The predictions from the two methods agree well with each other. The hyperbolic method was also used by Al-Shamrani (2005) to analyse the settlement data and the \(\delta_{ult}\) obtained was 17–2 cm, which was lower than that from either Asaoka’s method or the proposed method.

CONCLUSIONS

The Chapman–Richards model is adopted in this paper to best fit Terzaghi’s one-dimensional consolidation curve. The obtained formula fits the theoretical solutions well, with a regression coefficient of 0.9995 and errors less than 2%. The derived formula could be used as an observational method to predict the ultimate settlement of compressible soil undergoing one-dimensional consolidation, as well as to back-calculate the coefficient of consolidation of the soil.

The accuracy of the proposed observational method is verified against oedometer testing data and field settlement monitoring data. The settlement prediction made using the proposed method is more accurate compared with that using Asaoka’s method. The settlement prediction can become reasonably accurate when data in the range corresponding to the degree of consolidation up to 60% are available. The analysis shown in this paper also indicates the proposed method is not much affected by the choice of sampling interval \(\Delta t\). However, the number of sampling points \(N_{90}\) should be greater than 20 in order to achieve a higher regression coefficient for the least-squares linear regression for 90% degree of consolidation.

NOTATION

- **\(c_v\)** coefficient of vertical consolidation
- **\(H\)** drainage path
- **\(f_{bs}\)** number of samples to reach 95% degree of consolidation

**REFERENCES**


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