METHOD FOR ESTIMATION OF COEFFICIENT OF CONSOLIDATION FOR RADIAL FLOW FROM IN-SITU TIME - SETTLEMENT PLOTS

V. Venkata Charan¹, Madhav Madhira²

ABSTRACT

Excessive settlement is a major problem to deal with in construction of structures on compressible soils. Ground improvement using PVDs coupled with preloading can significantly shorten the time for primary consolidation. Coefficient of consolidation plays an important role in the estimation of time taken for the primary consolidation in case of clayey soils. Coefficient of consolidation for radial flow is estimated or determined from constant strain consolidation method (CRS), piezocone dissipation test, etc. In this paper a study is carried out to estimate the coefficient of consolidation for radial flow, \( c_r \), at an early stage of construction from in situ time-settlement plots. The method developed is based on degree of consolidation at the end of construction. The degree of consolidation, \( U_{Tc} \) at the end of construction, \( T_c \), is estimated from the plots of degree of consolidation, \( U_r \) versus time factor, \( T_r \) and plotted against \( T_c \) (Fig.1) for \( T_r = T_c \) for different values of \( n \). The coefficient of radial consolidation is then estimated from the value of time factor and “n” (the ratio of unit cell, \( d_e \), to that of the drain, \( d_w \)).

Fig.1 Variation of \( U_{Tc}\% \) with \( T_c \) for different values of \( n \)

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The proposed method is applied to back analyse actual time – settlement plots for different case histories, viz., Stockholm-Arlanda Airport, Suvarnabhumi International Airfield, Bangkok, Ska-Edeby Test Field. Estimated values of $c_r$ are compared with those given by the respective authors.

Keywords: Coefficient of consolidation for radial flow, PVDs, time – settlement plot, end of construction time.
METHOD FOR ESTIMATION OF COEFFICIENT OF CONSOLIDATION FOR RADIAL FLOW FROM IN-SITU TIME-SETTLEMENT PLOTS

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ABSTRACT: Excessive settlement is a major problem to deal with in construction of structures on compressible soils such as soft clays. Ground improvement using PVDs coupled with preloading can significantly shorten the time for primary consolidation. Coefficient of consolidation plays an important role in the estimation of time taken for the primary consolidation in case of clayey soils. In this paper a study is carried out to estimate the coefficient of consolidation for radial flow, \( c_r \), from in situ time-settlement plots. The method developed is based on degree of consolidation at the end of construction time which is related to the time factor corresponding to the end of construction for given value of “\( n \)” (the ratio of unit cell, \( d_e \), to that of the drain, \( d_w \)) which is then used for the estimation of coefficient of consolidation for radial flow. The coefficient of radial consolidation estimated by back analysis of actual in situ time–settlement plots are compared with those given by respective authors.

INTRODUCTION

Soft soils are treated generally with PVDs to accelerate consolidation settlement of soft normally consolidated clay layers. This system has been used successfully to improve foundation soils for embankments, airports and highways (Indraratna and Redana 2000; Li and Rowe 2002). It is important to note that for most soft clay deposits, the horizontal permeability is higher than the vertical one. Hence, rapid radial drainage accelerates the consolidation process (Jamiolkowski et al. 1983). The coefficient of consolidation for radial flow plays an important role in the estimation of the time taken for primary consolidation in case of fine grained soils. The duration for which a preload should be placed on the soft soil is an important parameter in the construction activity. The idea proposed in the paper involves estimation of the coefficient of consolidation for radial flow from in situ time–settlement plots.

Barron (1948) presented the first exhaustive solution to the problem of consolidation of a soil cylinder containing a central vertical drain. Barron's theory enables one to solve the problem of consolidation under two conditions, namely: (i) free strain with the vertical surface stress remaining constant but with non-uniform surface displacements during the consolidation process; and (ii) equal strain with non-uniform vertical surface stresses as

\[
\frac{\partial u}{\partial t} = c_r \left[ \frac{\partial^2 u}{\partial r^2} + \frac{1}{r^2} \left( \frac{\partial u}{\partial r} \right) \right]
\]

where \( u \) is the excess pore pressure at radial distance, \( r \), from the center of the unit cell and at time, \( t \), after an instantaneous increase of the total vertical stress, and \( c_r \) – the coefficient of consolidation for radial flow. Barron’s (1948) solution for equal strain case, monotonic loading, no smear and no well resistance is

\[
U_r = 1 - \exp \left( \frac{-8 T_r}{m} \right)
\]

where

\[
T_r = \left( \frac{\varepsilon_r t}{\sigma_v^2} \right)
\]

\[
m = \left( \frac{n^2}{n^2 - 1} \right) \ln n - \left( \frac{3n^2 - 1}{4n^2} \right)
\]
\[ n = \frac{\text{Diameter of equivalent soil cylinder (d_e)}}{\text{Equivalent diameter of the drain (d_w)}} \]  

(5)

d_e = 1.128S and 1.05S for drains installed in square and triangular patterns respectively and T_r – Non-dimensional time factor for radial consolidation.

The solution for consolidation under radial flow for equal strain, construction or ramp loading with no smear (Olson 1977) is

\[ U_r = \frac{T_r(1-\exp(-AT_r))}{A} \text{ (For } T_r \leq T_c) \]  

\[ U_r = 1 - \frac{1}{AT_c} \left( \exp(AT_c) - 1 \right) \exp\left(-AT_r\right) \text{ (For } T_r \geq T_c) \]  

(6)

(7)

Where T_c – non-dimensional time factor at the end of construction and

\[ A = \frac{2}{m} \]

Degree of consolidation, U_r at the end of construction (with radial flow) increases with time for construction, T_c and decreases with n. Longer the construction period, greater is U_r. U_r decreases with n, i.e., larger spacing of the PVDs.

\[ S_{r} = \frac{U_{r}T_{c}}{1 - U_{r}T_{c}} \]

Degree of Settlement/Consolidation at the End of Construction

The method is based on the degree of consolidation, \( U_{rT_c} \), at the end of construction time, T_c. The coefficient of radial consolidation, c_r, so determined corresponds to the end of construction time.

The degree of consolidation, \( U_{rT_c} \) at the end of construction, T_c, is estimated from the plots of degree of consolidation, U_r versus time factor, T_r and plotted against T_c (Fig.2) from Eq. 6 with \( T_r = T_c \) for different values of n.

Fig. 2 Variation of \( U_{rT_c}\% \) with T_c for different values of n.

Degree of consolidation, \( U_{rT_c} \) at the end of construction (with radial flow) increases with time for construction, T_c and decreases with n. Longer the construction period, greater is \( U_{rT_c} \).

Application of the Method

1. From a given time - settlement plot, the final settlement, S_f, is estimated using Asaoka or Hyperbola methods.

2. From the settlement, S_t, at the end of construction, t_c the degree of settlement, U_t, is then determined as

\[ U_{rT_c} = \frac{S_{t_c}}{S_f} \]  

(8)

3. The time factor, T_c, corresponding to the end of construction, is obtained from Fig. 2 from the
estimated value of $U_{RTC}$ and the known value of the ratio, $n$. The coefficient of consolidation with radial flow is then estimated from the known values of $t_c$, $T_c$ and $d_e (= c.S)$, the diameter of the unit cell; ($c$= 1.05 and 1.13 for triangular and square arrangements respectively and $S$ the spacing of drains), as

$$c_r = \frac{T_c \times d_e^2}{t_c} \quad (9)$$

**Application of the Method from Case Studies**

1. **Stockholm-Arlanda Airport**

At Stockholm-Arlanda Airport, different types of soil improvement techniques have been used. Among these, vertical drainage in combination with preloading has been used along the runway/taxiway in an area of 250,000 m² containing clay and organic deposits. The drain spacing and the preloading conditions were selected in order to achieve 95% primary consolidation within 12 months of loading. Thus, in order to achieve the goal, preloading has been carried out by means of 14–20 m of fill. The load of the fill has caused a relative compression of 22–29%, corresponding to total settlements of 1.6 – 2.6 m. Vertical drains were installed in equilateral triangular pattern with a drain spacing of 0.9 m. Hansbo (2005) based on Darcian flow estimated $c_r$ to be 2.6 m²/year.

**Fig. 3** Loading History and Settlement profile, Stockholm Arlanda, Sweden (Hansbo 2005)

For 100 mm by 4 mm Fiber drain of 0.9 m triangular spacing, $d_e = 1.05 s = 1.05 \times 0.9 = 0.945$ m. The equivalent diameter of the drain, $d_w = \frac{2(a+b)}{\pi} = 66.2$ mm. The ratio $n = \frac{d_e}{d_w} = 14.27$, $m = 1.93$ (Eq. 4)

2. **Suvarnabhumi International Airfield**

Bangkok, Thailand

In connection with the planning of a new international airfield in Bangkok, Thailand, three test areas were chosen to form a basis for the design of soil improvement by preloading in

**Fig. 4** Asaoka’s Plot for Estimation Final Settlement for Stockholm-Arlanda Project

The final settlement for drain is estimated from Asaoka plot (Fig. 4) as 2.8 m. Time of construction for the preloading = 171 days. Settlement at the end of construction was 2.2 m. The degree of consolidation, $U_{RTC}$, at the end of construction is $U_{RTC} = 2.2/2.8 = 78.6\%$. For $U_r = 78.6\%$ and $n = 14.27$, the time factor corresponding to end of construction, $T_c$ can be found to be 1.12 (Fig. 2). The coefficient of consolidation for radial flow is

$$c_r = \frac{1.12 \times 0.945^2}{171} = 2.13 \text{ m}^2/\text{year} \quad (\text{Eq. 9})$$
combination with vertical drains. The clay penetrated by the vertical drains is slightly overconsolidated with a preconsolidation pressure about 15–50 kPa higher than the effective overburden pressure. The clay below the tip of the drains is heavily overconsolidated.

The crest width of TS 3 is 14.8 m (square) and the bottom width 40 m. It is provided with approximately 10 m wide loading berm, 1.5 m thick. The fill placed on the area amounts to maximum of about 4.2 m, corresponding to a load of about 80kN/m$^2$. Vertical drains were installed to a depth of 12 m in a square pattern.

Consolidation characteristics of the clay deposit, determined by oedometer tests, can be summarized as follows (Airports Authority of Thailand, 1996; DMJM International, 1996): average coefficient of consolidation for virgin compression i.e., for stresses above the preconsolidation pressure, $c_v = 1.06 \text{ m}^2/\text{year}$, $c_r = 1.37 \text{ m}^2/\text{year}$.

For 100 mm by 4 mm Fiber drain of 1 m Square spacing, $d_e = 1.13 \text{ s} = 1.13 \times 1 = 1.13 \text{ m}$. The equivalent diameter of the drain, $d_w = \frac{2(a+b)}{\pi} = 66.208 \text{ mm}$. The ratio $n = \frac{d_e}{d_w} = 17.2$, $m = 2.10$ (Eq. 4)

![Fig. 5 Loading History and Settlement profile of Test Area 3, Bangkok, Thailand (Hansbo 2005)](image)

![Fig. 6 Asaoka’s plot for Estimation Final Settlement (a) Consolidation Settlement Curve (b) Total Settlement Curve for Bangkok Test Field, Thailand](image)

Final settlements and settlements at the end of construction for consolidation settlement and total settlement curves estimated from Asaoka plot (Fig. 6) are 1.51 m, 1.78 m and 0.86 m and 1.08 m respectively. Time of construction for preloading was 220 days.

The degree of consolidation, $U_{rTc}$, at the end of construction for consolidation settlement curve is $U_{rTc} = 0.86/1.51 = 56.9\%$. For $U_r = 56.9\%$ and $n = 17.2$, the time factor corresponding to end of construction, $T_c$ can be found to be 0.53 (Fig. 2). The coefficient of consolidation for radial flow is
\[ c_r = \frac{0.53 \times 1.13^2}{220} = 1.12 \text{ m}^2 / \text{year} \quad (\text{Eq. 9}) \]

The degree of consolidation, \( U_{rTc} \), at the end of construction for total settlement curve is \( U_{rTc} = 1.08/1.78 = 60.6\% \). For \( U_r = 60.6\% \) and \( n = 17.2 \), the time factor corresponding to end of construction, \( T_c \) can be found to be 0.6 (Fig. 2). The coefficient of consolidation for radial flow is

\[ c_r = \frac{0.6 \times 1.13^2}{220} = 1.27 \text{ m}^2 / \text{year} \quad (\text{Eq. 9}) \]

3. **Ska-Edeby Test Field**

Band drains, type Geodrain with paper filter were installed with 0.9 m spacing at Test Area V at Ska-Edeby. The initial load of 27 kN/m², was doubled after 3.5 years of consolidation.

**Fig. 7** Compression of the clay layer between 2.5 and 7.5 m depths at Ska-Edeby in Test Area V: (Hansbo 2005)

For 100 mm by 4 mm Geodrain at 0.95 m triangular spacing, \( d_e = 1.05 \), \( s = 1.05 \times 0.95 = 0.997 \) m. The equivalent diameter of the drain, \( d_w = \frac{2(a+b)}{\pi} = 66.2 \) mm. The ratio \( n = \frac{d_e}{d_w} = 15.07 \), \( m = 1.97 \) (Eq. 4)

**Fig. 8** Asaoka’s plot for Estimation Final Settlement for Ska-Edeby Test Field

The final settlement for drain treated ground is estimated from Asaoka plot (Fig. 8) as 315 mm.

Time of construction for the preloading = 40 days. Settlement at the end of construction was 15 mm. The degree of consolidation, \( U_{rTc} \), at the end of construction is \( U_{rTc} = 15/315 = 4.7\% \). For \( U_r = 4.7\% \) and \( n = 15.06 \), the time factor corresponding to end of construction, \( T_c \) can be found to be 0.024 (Fig. 2). The coefficient of consolidation for radial flow is

\[ c_r = \frac{0.024 \times 0.997^2}{40} = 0.217 \text{ m}^2 / \text{year} \quad (\text{Eq. 9}) \]

The values of coefficient of consolidation predicted by the proposed method are compared with the corresponding values given by Hansbo (2005). The predicted value for Stockholm site is slightly less while the value for SBIA is slightly more. The coefficient of consolidation for Ska-Edeby site is significantly lower (about 50%) compared to the value given by Hansbo (2005). It should be noted that the values given by Hansbo are obtained by curve fitting to the complete time-settlement plots.
Table 1 Summary of coefficients of consolidation for radial flow for different case studies by different methods.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Case study</th>
<th>Degree of consolidation at the end of construction (m²/year)</th>
<th>Hansbo (m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stockholm</td>
<td>2.13</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.12 (consolidation curve)</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>Bangkok</td>
<td>1.27 (total settlement curve)</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>Ska-Edeby</td>
<td>0.217</td>
<td>0.45</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Coefficient of consolidation for radial flow plays an important role in the estimation of the time taken for primary consolidation in case of clayey soils treated with PVDs. The coefficients of consolidation for radial flow at the end of construction estimated for Stockholm and Bangkok sites compare well with the estimated values of Hansbo (2005).

REFERENCES