Estimation of Non-homogeneities in in-situ Compressibility and Consolidation Parameters of Soft Ground

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ABSTRACT: In this study, compression index and coefficient of consolidation for radial flow at different depths are estimated from measured settlement – time plots from a project with PVDs to accelerate consolidation settlement of soft normally consolidated soils. The study identifies and quantifies non-homogeneity of the soft ground with respect to compression index and coefficient of consolidation for radial flow at different depths estimated by back-analysis from time-settlement plots reported from several depths for a given deposit.

1 INTRODUCTION

Soft soils are treated generally with PVDs to accelerate consolidation settlement of soft normally consolidated clay layers. Barron (1948) presented the solution for consolidation of a soil cylinder containing a central sand drain for equal strain case as

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

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 monotonic loading for no smear and no well resistance is

$$U_r = 1 - \exp\left(\frac{-8 * T_r}{m}\right) \quad (2)$$

where

$$T_r = \left(\frac{c_r * t}{d_e^2}\right) \quad (3)$$

$$m = \left(\frac{n^2}{n^2 - 1}\right)\ln(n) - \left(\frac{3n^2 - 1}{4n^2}\right) \quad (4)$$

$$n = \frac{\text{Diameter of equivalent soil cylinder}(d_e)}{\text{Equivalent diameter of drain}(d_w)} \quad (5)$$

d_e= 1.128S and 1.05S for drains installed in square and triangular patterns respectively and T_r – Non-dimensional time factor. Solution for consolidation under radial flow for construction or ramp loading with no smear (Olson 1977) is

For $T_r \leq T_c$, time factor, T_r, less than time factor at the end of construction, T_c

$$U_r = \frac{T_r - \frac{(1 - \exp(-AT_r)}{A}}{T_c} \quad (6)$$

For $T_r \geq T_c$, time factor, T_r, greater than time factor at the end of construction, T_c

$$U_r = 1 - \frac{1}{AT_c}(\exp(AT_c) - 1)\exp(-AT_r)) \quad (7)$$

where T_c -non-dimensional time factor at the end of construction and $A = \frac{2}{m}$

1.1 Coefficient of Consolidation for Radial Flow

The method for the estimation of coefficient o9f consolidation for radial flow is based on the degree of consolidation, U_{rTc}, at the end of construction time, T_c. The degree of consolidation, U_{rTc} at the end of construction, T_c, is determined and plotted against T_c (Fig.1) from Eq. 6 with T_r = T_c for different values of n.

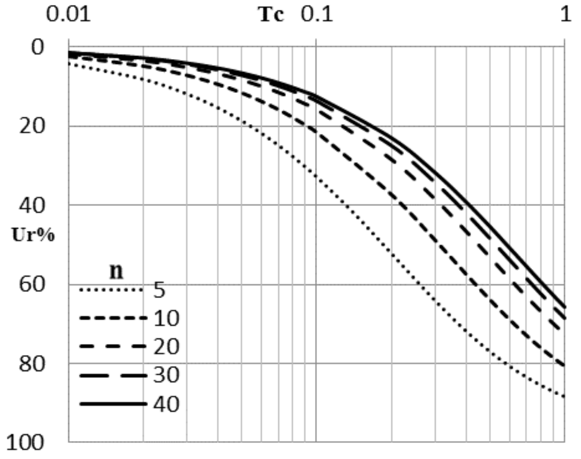

Fig. 1 Variation of U_{rTc} with T_c for different values of n.

Degree of consolidation, U_{rTc} at the end of construction (with radial flow) increases with T_r and decreases with n.

1.2 Application of the method

1. From a given time - settlement plot, the final settlement, S_f, is estimated using Asaoka (Asaoka 1978) or hyperbola (Tan 1993) methods. The settlement, S_{tc}, at the end of construction, i.e., at t_c and the value of degree of settlement, U_{rtc}, are then determined as

$$U_{rtc} = \frac{S_{tc}}{S_f} \tag{8}$$

2. The time factor corresponding to the end of construction, T_c is obtained from Fig. 1 for the estimated value of U_{rtc}. The coefficient of consolidation with radial flow is determined from the known values of t_c, T_c and d_e, as

$$c_r = \frac{T_c * {d_e}^2}{t_c} \tag{9}$$

1.3 Compression Index

Primary consolidation settlement for soft soils is estimated considering the soil to be either as normally consolidated or as overconsolidated based on its past history or Engineering Geology.

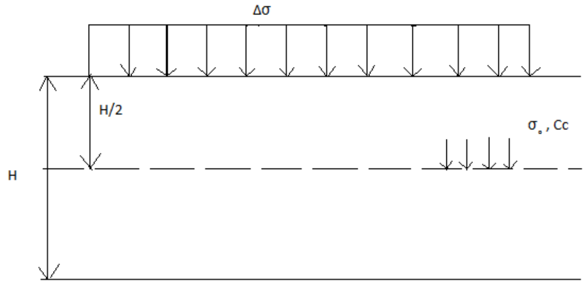

Fig. 2 Compressible stratum - single layer

Primary consolidation settlement, S, for a compressible strata considering it as a single layer (Fig. 2) is

For normally-consolidated soil

$$S = \frac{C_c * H}{1+e_0} * \log[\frac{\sigma' + \Delta\sigma'}{\sigma'_0}] \tag{10}$$

For overconsolidated soil

$$S = \frac{C_c * H}{1+e_0} * \log[\frac{\sigma' + \Delta\sigma'}{\sigma'_c}] + \frac{C_s * H}{1+e_0} * \log(OCR) \tag{11}$$

where C_c- compression index, C_s- recompression index, H- thickness, OCR- overconsolidated ratio, e_0 - initial void ratio, σ'_c - preconsolidation pressure σ' - effective overburden pressure at mid-layer, $\Delta\sigma'$ - stress increase. Re-arranging the terms as Compression Index, C_c, of each layer is

For normally consolidated soil

$$C_c = \frac{\Delta S * (1+e_0)}{\Delta H * \log\left(\frac{\sigma'_0 + \Delta\sigma'}{\sigma'_c}\right)} \tag{12}$$

For overconsolidated soil

$$C_c = \frac{\Delta S * (1+e_0)}{\Delta H\left[\frac{C_s}{C_c} * \log\left(\frac{\sigma'_c}{\sigma'_0}\right) + \log\left(\frac{\sigma'_0 + \Delta\sigma'}{\sigma'_c}\right)\right]} \tag{13}$$

Similar expressions are written for estimation of compression index for each sub-layer and the compression index, C_c, for each particular sub-layer is estimated from the known values of 'ΔS' of that particular sub-layer. The non-homogeneity of the deposit in terms of compression index is then identified and quantified from the compression indices for all the sub-layers.

Case record of construction of Suvarnabhumi International Airport (SBIA) is examined for the estimation of in situ compression index and coefficient of consolidation for radial flow. Typical soil profile in the Bangkok plain is shown in Fig. 3.

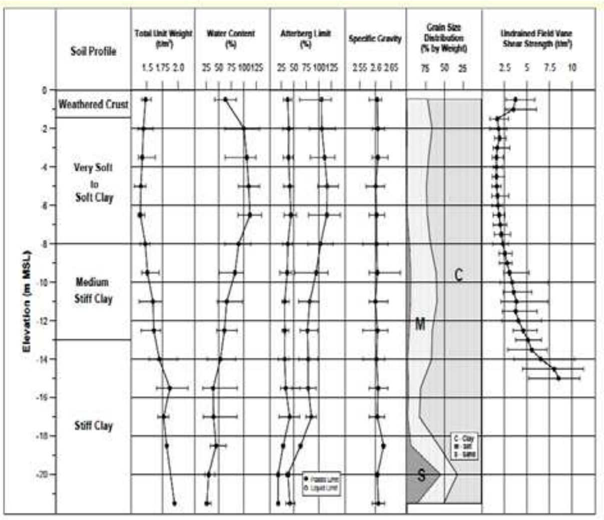

Fig. 3 Typical Soil Profile in SBIA (after Balasubramaniam et al. 2007)

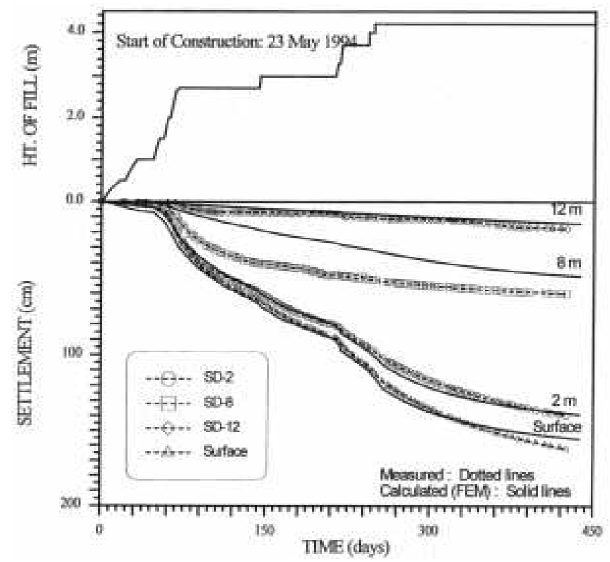

Fig. 4 Settlements vs time at Different Depths at SBIA site (after Balasubramaniam et al., 2007)

Preloading with PVDs was adopted for this project. Surface and deep settlement gauges, pneumatic and hydraulic piezometers, inclinometers were employed. Settlements at different depths and different time intervals were read using these settlement gauges (Fig. 4).

2. RESULTS AND DISCUSSION

Ultimate or final settlements at the surface, and at depths of 2 m, 8 m and 12 m are read from Fig. 5. Settlement of each sub-layers are estimated as difference between ultimate settlements of two consequent depths as shown in the Table 1. Compression index of each sub-layer is estimated based on the given soil properties (Fig. 3).

Table 1. Estimation of Compression Index for Different Sub-layers

Z (m)	S_{ULT} (m)	ΔS (m)	ΔH (m)	Z_0 (m)	σ' (kPa)	C_c
0	1.5					
		0.2	2	1	4.8	0.221
2	1.3					
		0.7	6	5	23	0.742
8	0.6					
		0.4	4	10	47	0.732
12	0.2					
		0.2	3	13.5	98	0.53
15	0					

Table 2. Compression Index of Each Sub-Layer

Sub-Layer (m)	Z (m)	C_c
0 to 2	1	0.221
2 to 8	5	0.742
8 to 12	10	0.732
12 to 15	13.5	0.53

Variation of compression index with depth is shown in Fig. 5. Compression index of top layer (0 to 2.0 m) is relatively low possibly due to desiccation. This reduction in compression index is quantified in terms of pseudo-OCR estimated using Eq.13. It is presumed that the desiccated layer initially was normally consolidated with the same value of compression index as the layer below, i.e. 0.742 which got reduced to 0.221 as a consequence of alternate heating and cooling and alternate wetting and drying. Pseudo-OCR of the desiccated layer is estimated for different values of 'C_s/C_c' in Eq. 13 to match with the compression index of the normally consolidated lower layer as given in Table 3.

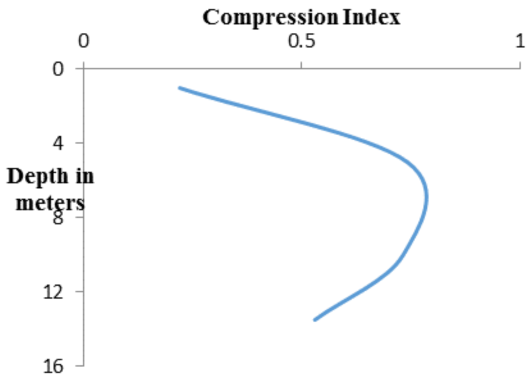

Fig. 5 Compression Index verses Depth at SBIA site

Table 3. Estimation of Pseudo-OCR

Pseudo-OCR	C_s/C_c=0.05	C_s/C_c=0.1	C_s/C_c=0.15
2	0.286	0.281	0.277
3	0.344	_	_
5	0.465	_	_
7	0.604	_	_
8	0.686	_	_
9	0.779	0.688	0.615
10	_	0.765	0.673
11	_	_	0.735

Table 4. Pseudo-OCR of Top Layer

C_s/C_c	Pseudo-OCR
0.05	8.6
0.1	9.7
0.15	11.1

Values of pseudo-OCR are obtained as a function of the assumed ratio of C_s/C_c (Table 4).

The diameter, d_e, of the unit cell for 1.0 m spacing in square pattern is 1.13 m. Equivalent diameter, d_w, of the drain, 100 mm by 10 mm, is 66.2 mm. The ratio n = d_e/d_w = 17.06 (Eq. 5), m = 2.09 (Eq. 4). Time of construction for the preload is 23.5 days. Final settlements and settlements at the end of construction for thicknesses of 0-8 m, 0-12 m and 0-16 m drain treated areas are 54 cm, 122 cm and 125 cm and 11.5 cm, 20 cm and 20 cm respectively. The degrees of consolidation, U_{rtc}, at the end of construction period for the depth ranges of 0-8 m, 0-12 m and 0-16 m, are respectively 21.3 (=11.5/54), 16.4 (=20/122) and 16 (=20/125). The corresponding time factors for the end of construction were estimated with the calculated values of U_{rtc} and n equal to 17, as 0.13, 0.097 and 0.094 for the three depth ranges. The corresponding coefficients of consolidation with radial flow are 2.5 m^2/yr, 1.92 m^2/yr and 1.86 m^2/yr (Table 5) and Fig. 6.

Table 5. Summary of the Results from Case Study

Thickness (m)	Coefficient of consolidation for radial flow c_r (m^2/year)
0-8	2.5
0-12	1.92
0-16	1.86

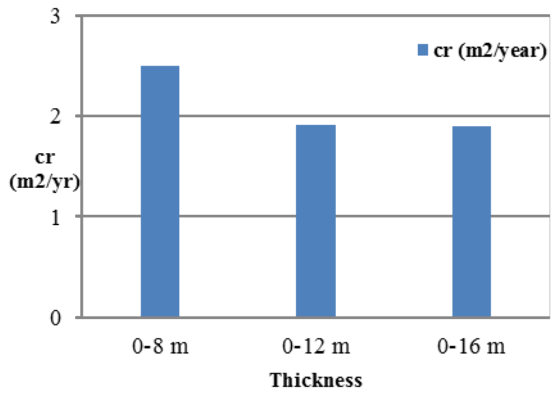

Fig. 6 Coefficient of consolidation with radial flow

3 CONCLUSIONS

In situ compression index and in situ coefficient of consolidation with radial flow are estimated by back-analysis from settlement-time plots available for different depths. Relatively lower value of compression index for the top desiccated layer was concluded as due to desiccation and quantified using pseudo-OCR.

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