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Relationship Between Various Consolidation Parameters of Compressible Soils

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Abstract. Consolidation of problematic soils such as soft or compressible soils with high clay content can be overcome by preloading along with Prefabricated Vertical Drains (PVDs) which is one of the most common techniques used over the past few years. Parameters that influence consolidation or rate of settlement at the site are coefficient of consolidation for horizontal/radial flow, smear effects such diameter of and permeability of remolded or disturbed soil in the smear zone. In this paper, degree of consolidation at the end of construction (U_{tc}), final settlements, S_{fA},fromAsaoka plots for degree of consolidation with time factor, under ramp loading with smear effects (s, the ratio of diameter of smear zone to that of drain, and k_h/k_s,the ratio of permeability on in situ soil to that of soil in the smear zone), have been developed for different unit cell diameter ratios, n, and time factors,T_c,corresponding to end of construction,. A new method for the estimation of in situ parameters such as C_r, s and k_h/k_s of the smear zone from the in situ measured time- settlement plot, is proposed.

Keywords: PVDs, Consolidation parameters; Unit cell; Smear; Degree of consolidation at the end of construction; Asaoka method

1 Introduction

Soft soils are often encountered along coastal regions, swampy areas and deltas all over the world, because of which construction of any infrastructure project on such soils is indeed a challenge. Consolidation of soft soils is mostly achieved through vertical drains which are coupled with preloading.Based on the one-dimensional consolidation theory, Asaoka[2] proposed a new approach to evaluate the coefficient of consolidation for vertical flow, c_v along with final settlement, S_f. Case history of Changi East Reclamation, Singapore comprising of vertical drains coupled with preloading was studied and presented by Arulrajah et al. [1] .Chung et al [3] presented various case studies which are associated with vertical drains with preloading like Chek Lap Kok airport, Busan Airport and Changi airport in their research work. Adverse effects such as smear and permeability ratio affect the consolidation in an unfavorable mannerby delaying the settlement rate. So, it is important to estimate these parameters that affect the consolidation rate and time in soft soils. The objective of the paper is to analyze and estimate the in-situ consolidation parameters smear ratio(s), permeability ratio(k_h/k_s) and coefficient of consolidation (C_h) from the available time-settlement data. Monitored data of time-settlement data from Indraratna et al.[6] are analyzed and presented.

2 Methodology

Theoretical values of degree of consolidation, U_{tc}, at the end of construction are obtained from Olson [8] for the consolidation with flow in the radial direction for ramploading as

$$U_{tc} = [T_c-(1-\exp(-AT_r)/A]/T_c \tag{1}$$

where

$$F(n) = (n^2/n^2-s^2)\ln(n/s) - ¾ + (s^2/4n^2) + k_h/k_s\,(n^2-s^2/n^2)\ln(s) \tag{2}$$

diameter ratio, $n = d_e/d_w$, d_e and d_w are the diameters of the drain well and influence zone respectively, smear ratio,$s = r_s/r_w$,r_s and r_w are the radii of smear zone and drain well respectively, $T_r = c_r.t/d_e^2$- dimensionless time factor, $T_c= c_r.t_c/d_e^2$- dimensionless time factor for time, t_c, at the end of construction, F(n) - function of n and s,k_h/k_s-permeability ratio and $A=20/F(n)$.T_c is calculated from the Eq. 1 with $T_r = T_c$ for different diameter ratios and different smear ratios.Knowing T_c, the coefficient of consolidation, c_r for flow in radial direction is determined as

$$c_r = (T_c*d_e^2)/t_c \tag{3}$$

Time-settlement plotsare shown in Fig. 1 of different sections from Indraratna et al. [6] who demonstrated the effectiveness of vacuum coupled surcharge loading system overconventional surcharge loading. All the curves from time versus settlement are digitized and analyzed for different time intervals.

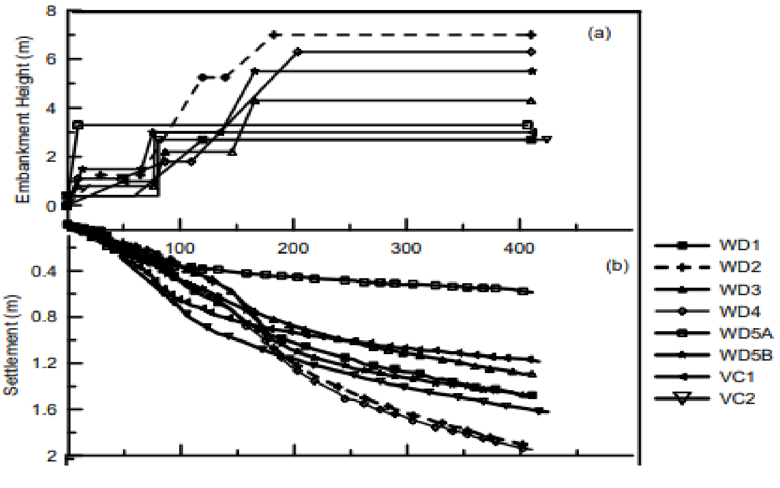

Fig. 1. Time-Settlement plot of staged construction (after Indraratna et al. [6])

In the new method, Final settlements, S_{fA} are estimated from the digitized data of time-settlement plots for different sections based on Asaoka(1978). Based on the settlement, S_c corresponding to the time at the end of first stage of ramp loading, t_c, the degree of consolidation, U_{tc}, at the end of construction is estimated for different diameter ratios, n. U_{tc} is plotted with respect to 's', and smear ratio is interpolated corresponding to 'n' U_{tc} is also plotted against T_c for different smear ratios, s. For a given 'n', T_c is obtained through interpolation. Same procedure is repeated for determining the permeability ratio, k_h/k_s and the corresponding T_c. The estimated coefficients of consolidation are compared with those of the Indraratna et al. [6]. Details such as drain type, diameter of drain well (d_w), equivalent diameter of the influence zone (d_e), spacing between the drains (S), diameter ratio (n), time at the end of construction (t_c) for the sections from Indraratna et al.[6] are extracted from Fig. 1.

3 Case study

Indraratna et al.[6] compared time-settlement responses between consolidation with vacuum surcharge preloading and conventional surcharge loadingat seven different sectionsand found that consolidation due radial flow is faster and lateral displacements are less in the former (vacuum surcharge loading) than the latter.In this study, typically, two types of drains i.e., circular and band shaped(100×4)mm with spacing of the drains rangingbetween 1.1 to 1.3m were used. Drains were laid in square pattern and the diameter of equivalent influence zone/unit cell, d_e, is obtained. The parameters are listed in Table 1.

Table 1. Drain type, spacing, S, diameter, d_w,of drain , and diameter, d_e, of unit cell, $n=d_e/d_w$ and time, t_c, at the end of construction (after Indraratna et al. [6])

Section	Drain type	Spacing	d_e (m)	d_w (m)	n	Time, t_c(days)
WD1	Circular 34	1.1	1.243	0.034	36	120
WD2	Circular 34	1.3	1.469	0.034	43	180
WD3	Band drains	1.1	1.243	0.065	19	160
WD4	Band drains	1.3	1.469	0.065	22	200
WD5B	Band drains	1.1	1.243	0.065	19	160
VC1	Circular 34	1.2	1.356	0.034	40	80
VC2	Circular 34	1.23	1.389	0.034	40	80

3.1 Validation

The proposed method is applied and validated for different sections mentioned in Indraratna et al [6]. A typical Asaokaplot for the section VC1 is shown in Fig. 2 withdiameter ratio, n of 36 with spacing, S as 1.1m.The final settlement, S_{fA} is obtained as 1.2m.

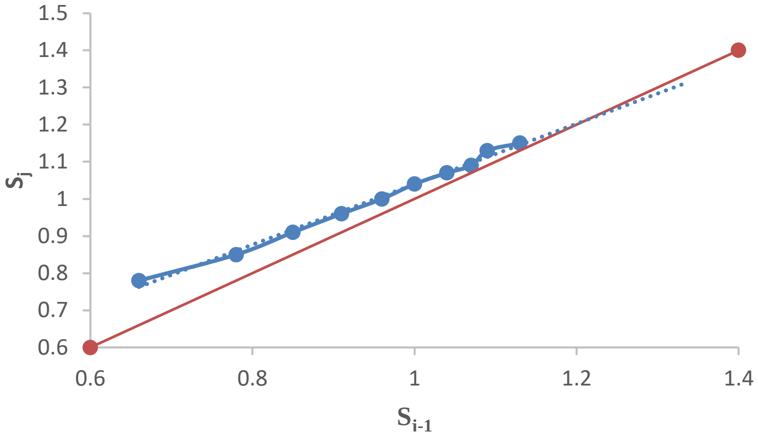

Fig.2. Asaoka plot for section VC1

Figs. 3 through 6 show plots drawn between U_{tc} and s for diameter ratio (n) varying between 10 to 40 for different time factors, T_c, at the end of construction. In similar way, plots for different 'T_c' values for varying 'n' are drawn. 's' is estimated through interpolation with 'n' corresponding to the obtained U_{tc} value.

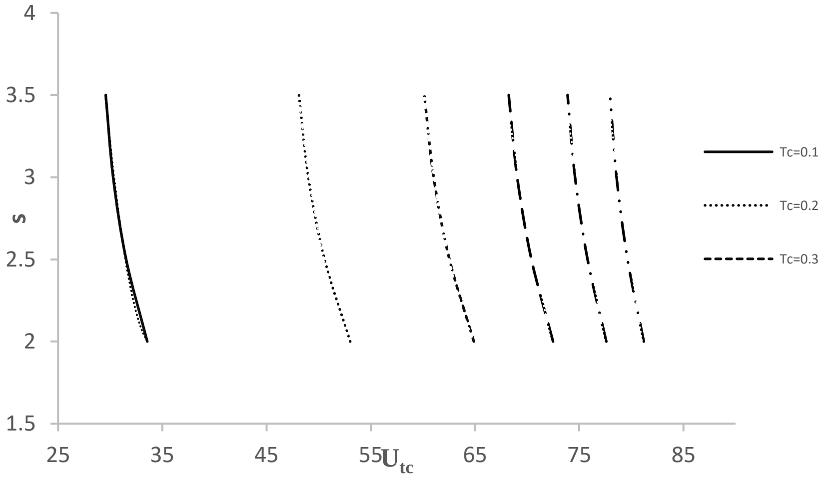

Fig. 3. U_{tc} vs s for n=10

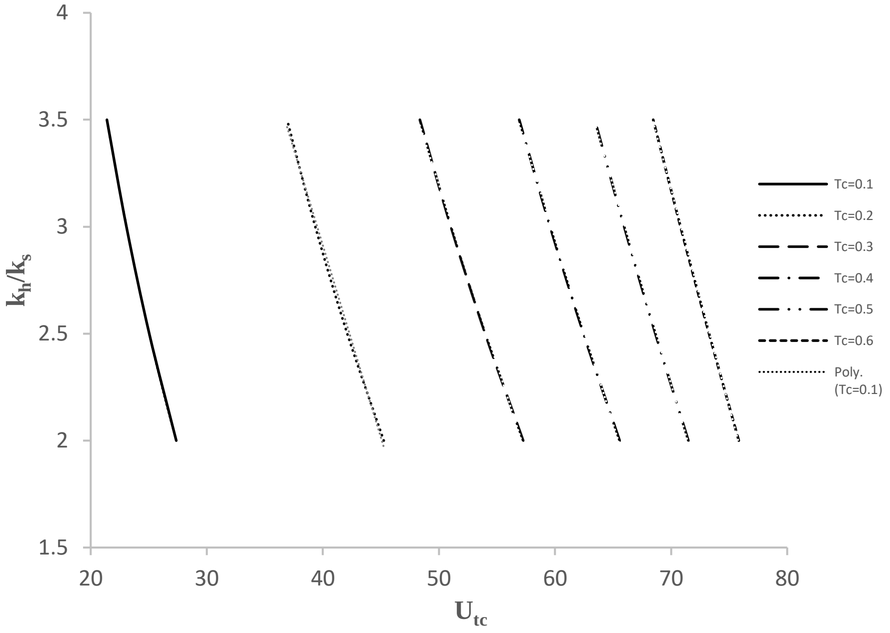

Fig. 4. U_{tc} vs s for n=20

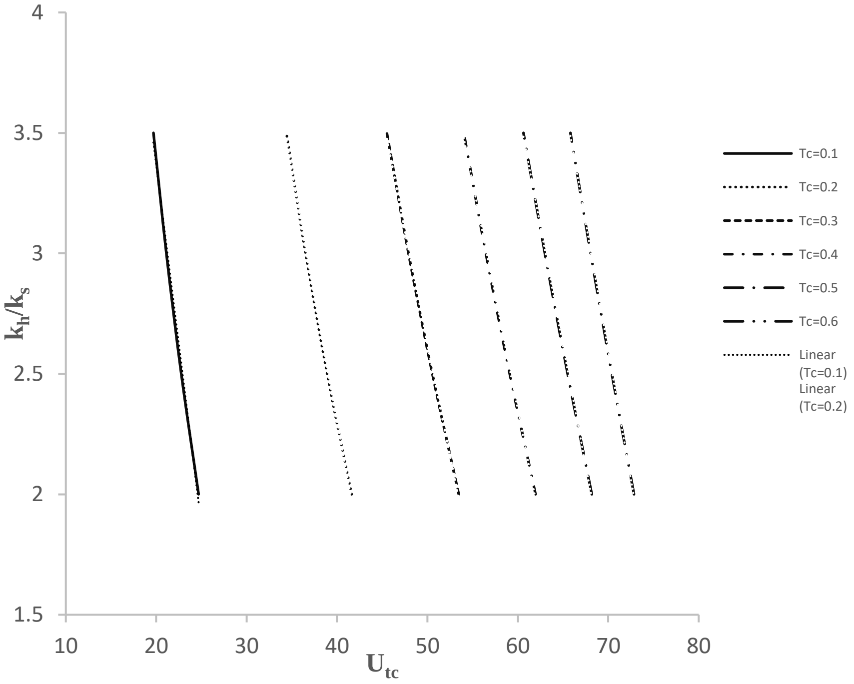

Fig. 5. U_{tc} vs s for n=30

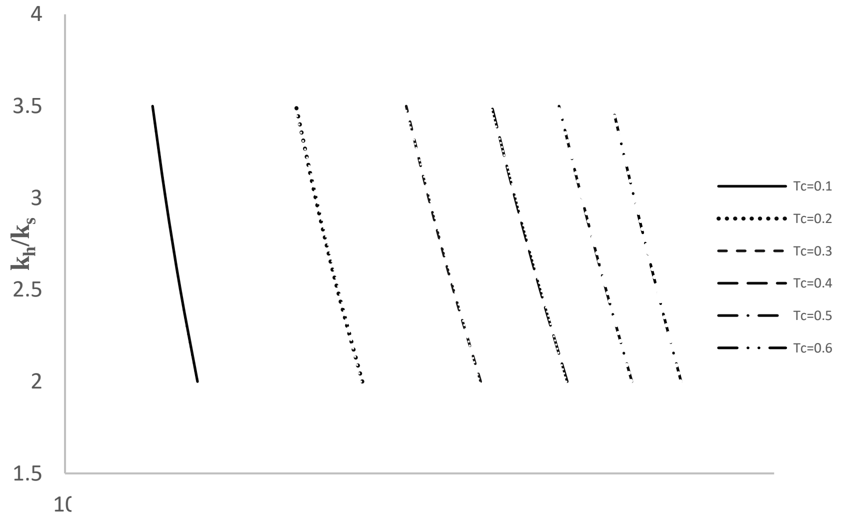

Fig. 6. U_{tc} vs s for n=40

Fig. 7 is a typical plot between time factor, T_c, and degree of consolidation, U_{tc}, at the end of construction for diameter ratios (n) ranging from 10 to 40 for smear ratio, s=2. For different diameter ratios, similar plots are drawn for 's' varying from 2.5 to 3.5. T_c is obtained through interpolationfor a given 's', corresponding to the obtained $U_{tc}$and for the known 'n' value.

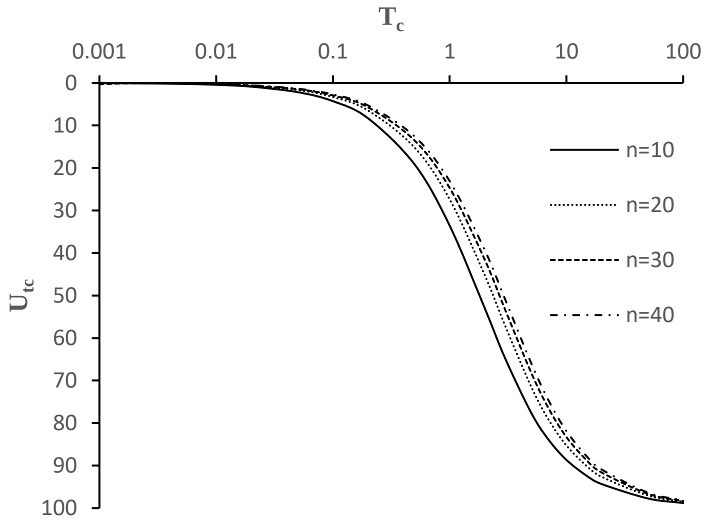

Fig. 7. T_c vs U_{tc} for different 'n' under s=2

Fig. 8 through 11 show typical plots drawn between U_{tc} and k_h/k_s for different diameter ratios (n) varying between 10 to 40 for different time factors, T_c, at the end of construction, Similarly, plots for different 'T_c' for varying 'n' are drawn. 'k_h/k_s' value is estimated through interpolation of 'k_h/k_s' with 'n' corresponding to the obtained U_{tc} value.

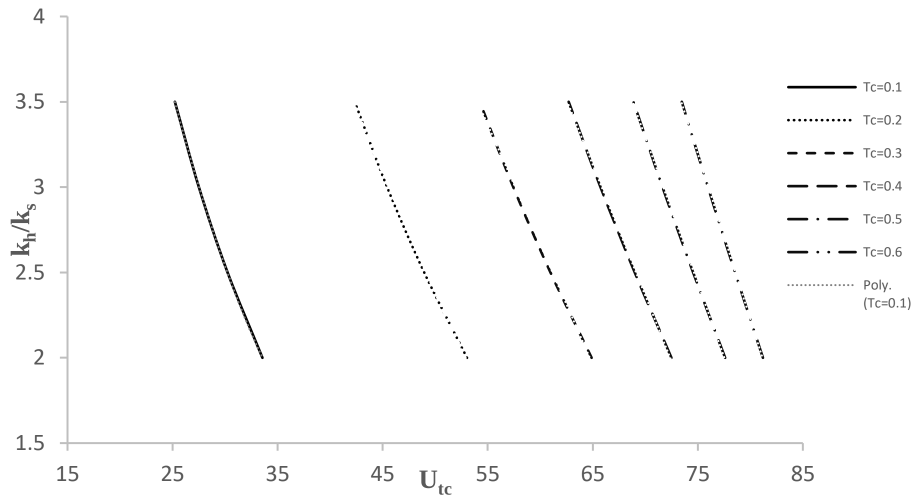

Fig. 8. U_{tc} vs k_h/k_s for n=10

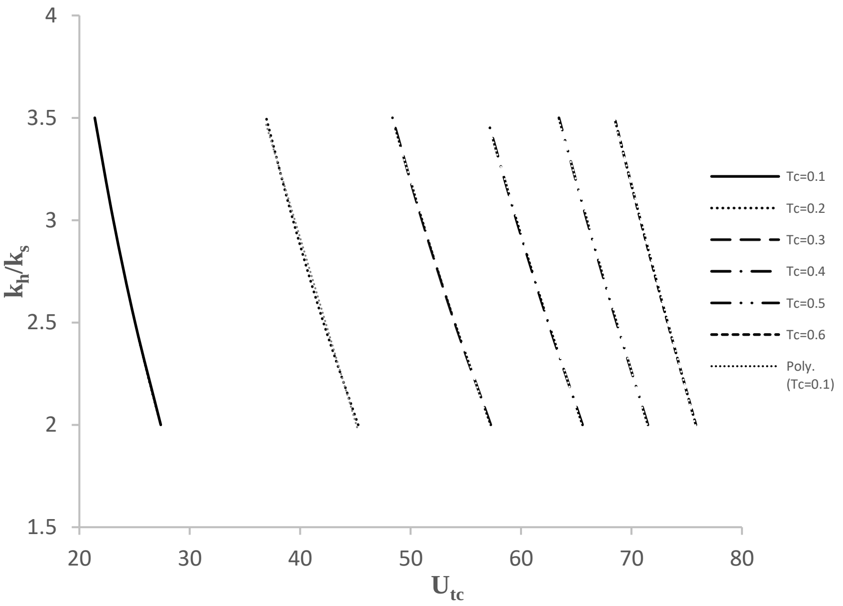

Fig. 9. U_{tc} vs $k_h/k_s$for n=20

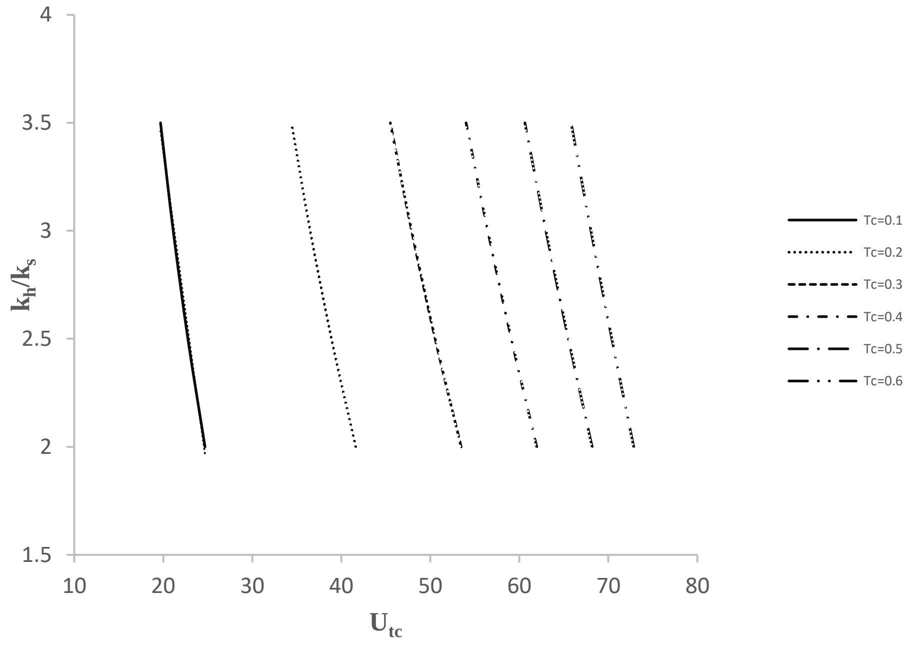

Fig. 10. U_{tc} vs k_h/k_s for n=30

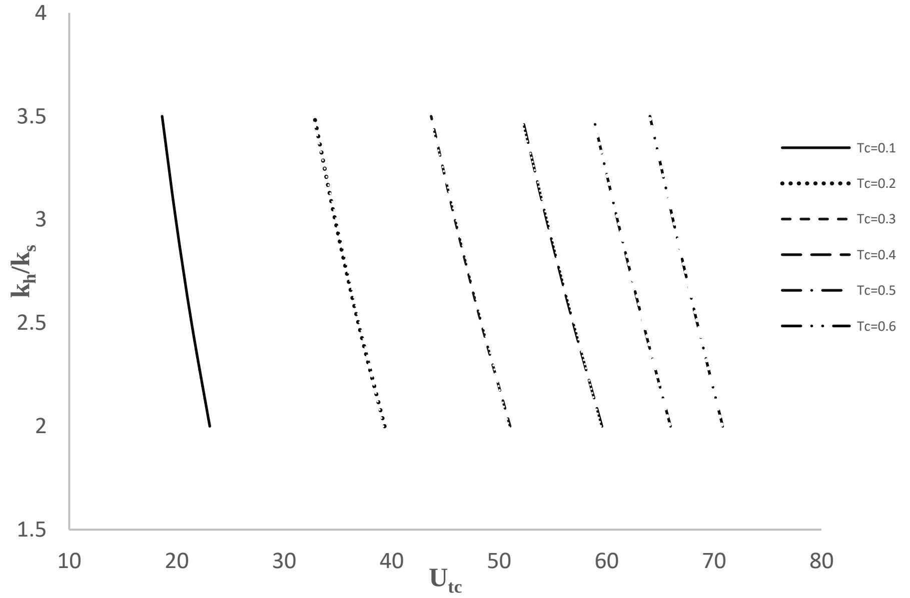

Fig. 11. U_{tc} vs $k_h/k_s$for n=40

Fig. 12 is a typical plot drawn between time factor, T_c, at the end of construction and degree of consolidation, U_{tc}, at the end of construction for diameter ratios (n) ranging from 10 to 40 for permeability ratio, k_h/k_s=2. Similar plots are drawn for 'k_h/k_s' values varying from 2.5 to 3.5 for varying diameter ratios. T_c is estimated for a given 'k_h/k_s', through interpolation of T_c and n corresponding to U_{tc}

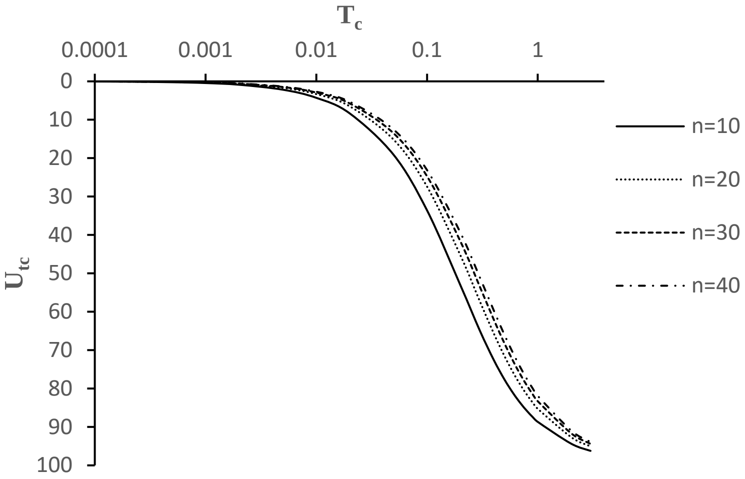

Fig. 12. T_c vs U_{tc} for different 'n' under k_h/k_s=2

Results obtained are tabulated in Tables 2 and 3. $U_{tc}$is obtained from settlement, S_c corresponding to the time, t_c, at the end of first construction loading and final settlement. Smear ratio and time factor at the end of construction are estimated or determined from Figs. 3 through 7. The coefficient of consolidation ,c_{rTc} is determined from Eq.3. Similarly, permeability ratio, k_h/k_s, and the corresponding time factor, T_c at the end of construction are from Figs. 8 through 12. The coefficient of consolidation, c_{rTc}, is calculated from Eq. 3.

Table 2. Final Settlement, S_{fA}, Degree of consolidation, U_{tc}, at the end of construction, Smear ratio(s), Permeability ratio (k_h/k_s) and Time factor, T_c, at the end of construction

Section	S_c (m)	S_{fA} (m)	U_{tc} (%) (S_c/S_{fA})	S	T_c	k_h/ks	T_c
WD 1	0.6	1.6	38	2.1	0.18	2.1	0.19
WD 2	1.1	2.3	50	2.3	0.32	2.2	0.33
WD 3	0.9	1.4	64	2.1	0.38	1.9	0.37
WD 4	1.3	2.4	54	2.0	0.27	2.3	0.28
WD 5B	0.9	1.6	56	1.8	0.265	1.9	0.265
VC 1	0.5	1.2	42	3.0	0.25	2.5	0.24
VC 2	0.6	1.7	34	3.5	0.22	3.0	0.21

Table 3. Coefficients of consolidation (c_r)

Section	C_r ($\times 10^{-3}$) (m^2/year) (Indraratna)	C_r T_c ($\times 10^{-3}$) (m^2/year) (for s)	C_r T_c/C_r (for s)	C_r T_c ($\times 10^{-3}$) (m^2/year) (for k_h/k_s)	C_r T_c/C_r (k_h/k_s)
WD 1	1.16	0.84	0.80	0.80	0.70
WD 2	1.31	1.38	1.05	1.42	1.08
WD 3	0.89	1.33	1.40	1.30	1.40
WD 4	1.02	1.04	1.02	1.08	1.06
WD 5B	0.90	0.92	1.03	0.92	1..03
VC 1	1.70	2.07	1.20	2.02	1.10
VC 2	1.41	1.90	1.30	1.82	1.30

Ratio of coefficient of consolidation (c_{rTc}) to the coefficient of consolidation, c_r (from Indraratna et al. [6]) ranges between 0.8 to 1.4and 0.7 to 1.4 for different permeability and smear ratios (Table 3).

4 Conclusions

As a well-known fact, vertical drains coupled with preloading is an efficacious method to expedite the consolidation by promoting radial flow. In this paper, the crucial factors that control the performance of vertical drains including the phenomenon of smear zone along with the permeability ratio were discussed. A new method to estimate the in-situ parameters, viz., smear ratio (s), permeability ratio (k_h/k_s) and coefficient of radial consolidation (c_r)from the time versus settlement plots is proposed. The proposed method is analyzed and illustrated through a well-documentedcase history, reported by (Indraratna et al. [6]. Time factors, T_c, at the end of construction obtained from the plots corresponding to smear (s) and permeability (k_h/k_s) ratios are nearly the same.Thecoefficients of radial consolidation (c_{rTc}) obtained from both the approaches are close and compare well with those of Indraratna et al.[6].

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