Relationship Between Various Consolidation Parameters of Compressible Soils

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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 [1] 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. [2]. 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 manner by 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. [4] are analyzed and presented.

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2 Methodology

Theoretical values of degree of consolidation, U_{tc}, at the end of construction are obtained from Olson [5] for the consolidation with flow in the radial direction for ramp loading as

$$U_{\text{tc}} = T_{\text{c}} - \left[(1 - \exp(-AT_{\text{r}})/A)\right]/T_{\text{c}} \tag{1}$$

where

$$F(n) = \left(n^2/n^2 - s^2\right)\ln(n/s) - {}^3\!/_4 + \left(s^2/4n^2\right) + k_{\text{h}}/k_{\text{s}}\left(n^2 - s^2/n^2\right)\ln(s) \tag{2}$$

diameter ratio, $n = d_{\text{e}}/d_{\text{w}}$, d_{e} and d_{w} are the diameters of the drain well and influence zone respectively, smear ratio, $s = r_{\text{s}}/r_{\text{w}}$, r_{s} and r_{w} are the radii of smear zone and drain well, respectively, $T_{\text{r}} = c_{\text{r}} \cdot t/d_{\text{e}}{}^2$—dimensionless time factor, $T_{\text{c}} = c_{\text{r}} \cdot t_{\text{c}}/d_{\text{e}}{}^2$—dimensionless time factor for time, t_{c}, at the end of construction, $F(n)$—function of n and s, $k_{\text{h}}/k_{\text{s}}$—permeability ratio and $A = 20/F(n)$. T_{c} is calculated from the Eq. 1 with $T_{\text{r}} = T_{\text{c}}$ 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

$$c_{\text{r}} = \left(T_{\text{c}} * d_{\text{e}}^2\right)/t_{\text{c}} \tag{3}$$

Time-settlement plots are shown in Fig. 1 of different sections from Indraratna et al. [4] who demonstrated the effectiveness of vacuum coupled surcharge loading system over conventional surcharge loading. All the curves from time versus settlement are digitized and analyzed for different time intervals.

In the new method, Final settlements, S_{fA} are estimated from the digitized data of time-settlement plots for different sections based on Asaoka [1]. 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, $k_{\text{h}}/k_{\text{s}}$ and the corresponding T_{c}. The estimated coefficients of consolidation are compared with those of Indraratna et al. [4]. 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. [4] are extracted from Fig. 1.

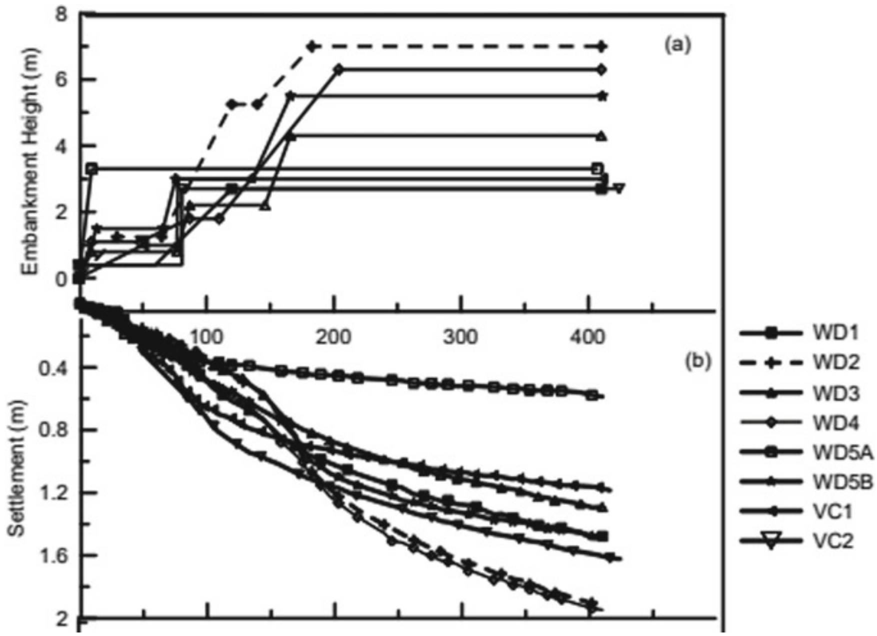

Fig. 1 Time-settlement plot of staged construction (after Indraratna et al. [4])

3 Case Study

Indraratna et al. [4] compared time-settlement responses between consolidation with vacuum surcharge preloading and conventional surcharge loading at seven different sections and 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 ranging between 1.1 and 1.3 m 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.

3.1 Validation

The proposed method is applied and validated for different sections mentioned in Indraratna et al. [4]. A typical Asaoka plot for section VC1 is shown in Fig. 2 with diameter ratio, n of 36 with spacing, S as 1.1 m. The final settlement, S_{fA} is obtained as 1.2 m.

Figures 3, 4, 5 and 6 show plots were drawn between U_{tc} and s for diameter ratio (n) varying between 10 and 40 for different time factors, T_c, at the end of

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. [4])

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

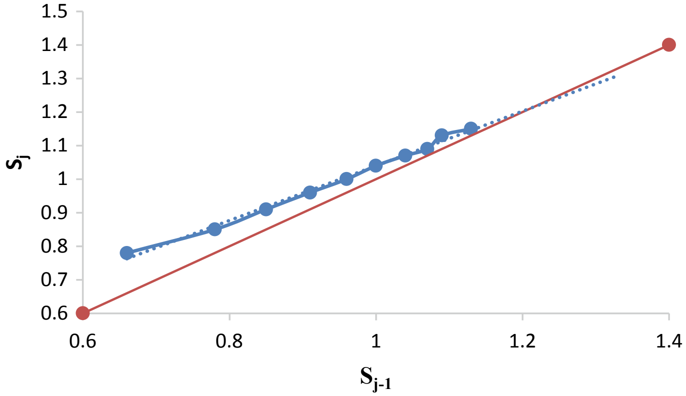

Fig. 2 Asaoka plot for section VC1

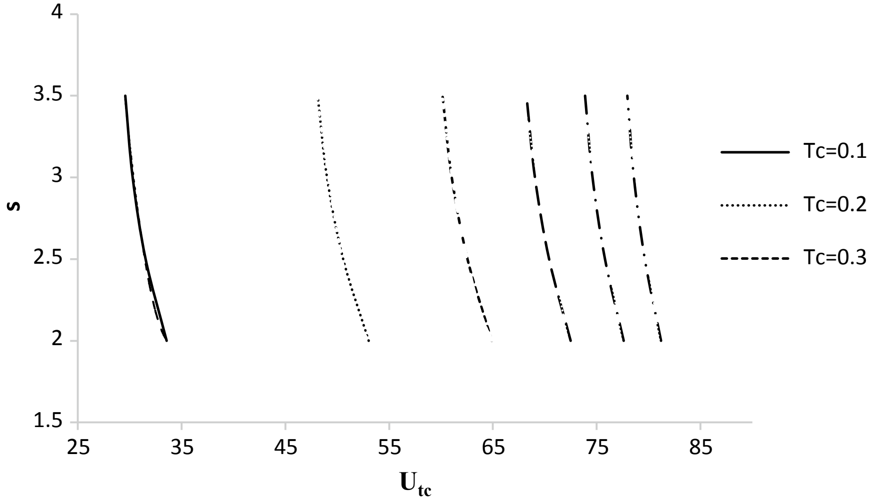

Fig. 3 U_{tc} versus s for $n = 10$

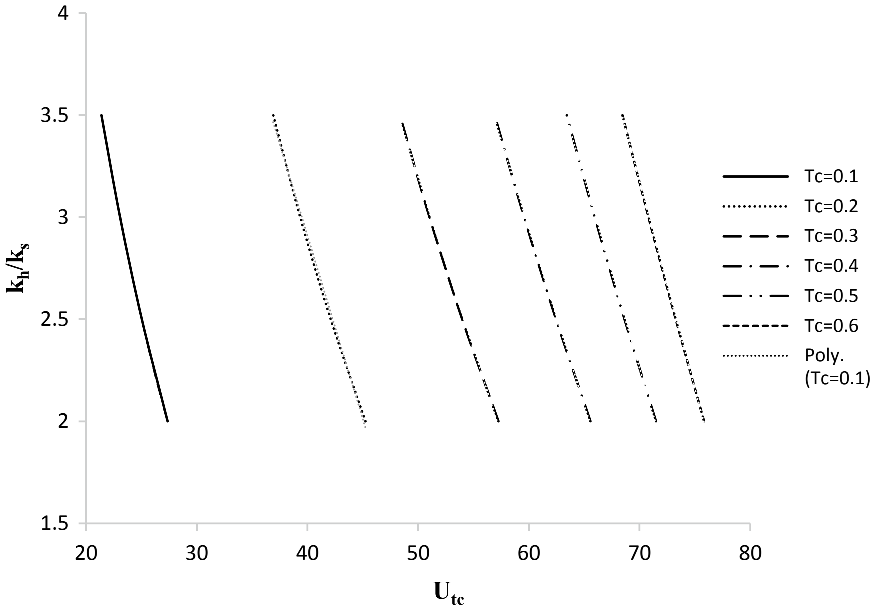

Fig. 4 U_{tc} versus s for $n = 20$

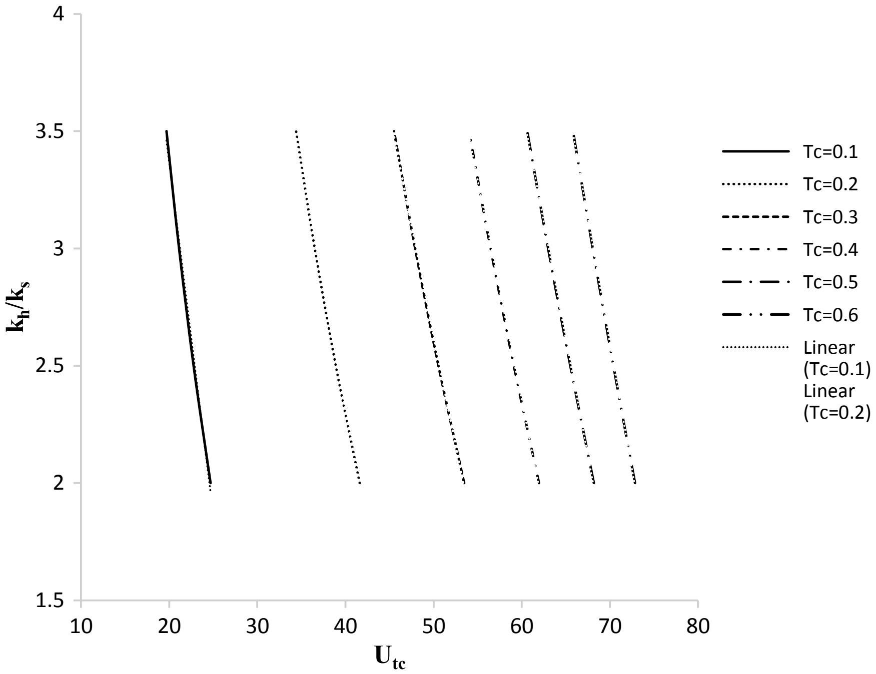

Fig. 5 U_{tc} versus s for $n = 30$

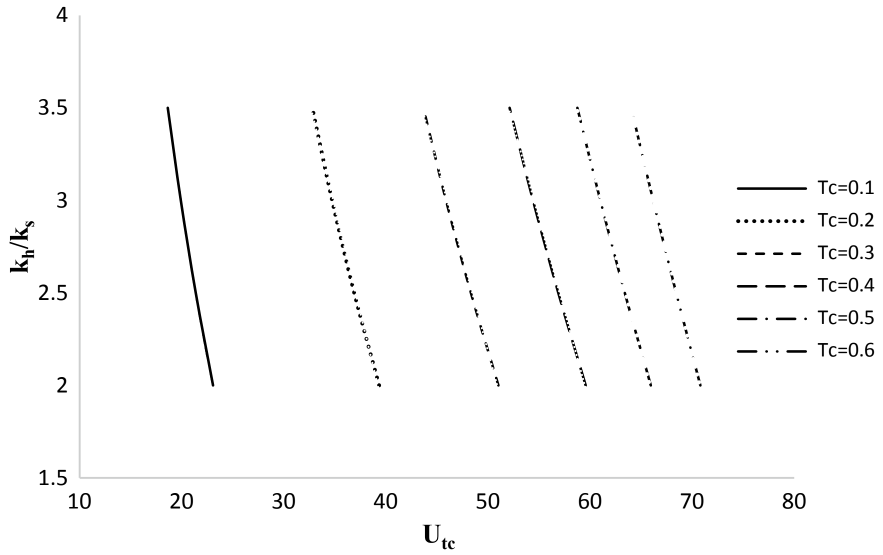

Fig. 6 U_{tc} versus s for $n = 40$

construction. In a 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.

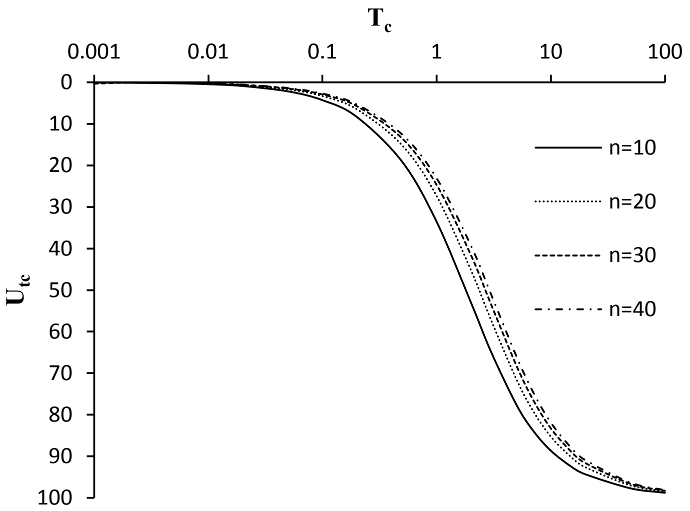

Fig. 7 T_c versus U_{tc} for different 'n' under $s = 2$

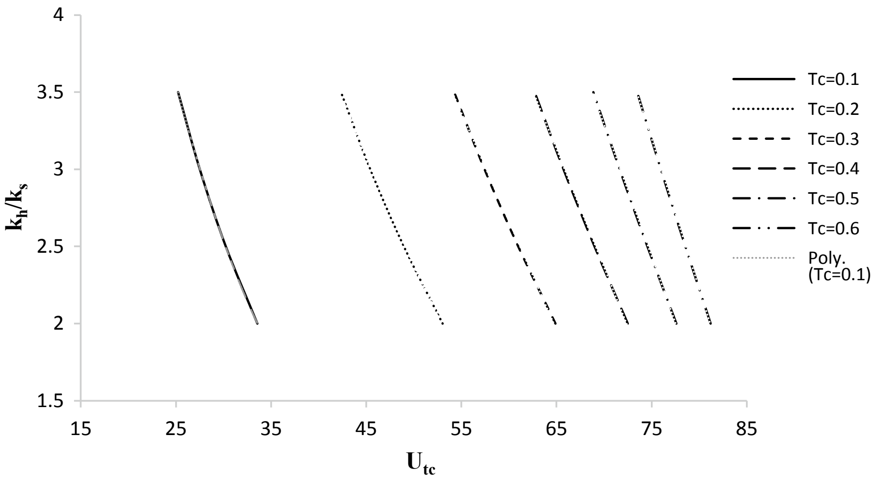

Fig. 8 U_{tc} versus k_h/k_s for $n = 10$

Figure 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 interpolation for a given 's', corresponding to the obtained U_{tc} and for the known 'n' value.

Figures 8, 9, 10 and 11 show typical plots drawn between U_{tc} and k_h/k_s for different diameter ratios (n) varying between 10 and 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.

Figure 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}.

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, 4, 5, 6 and 7. The coefficient of consolidation, $c_r\ T_c$ 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, 9, 10, 11 and 12. The coefficient of consolidation, $c_r\ T_c$, is calculated from Eq. 3.

Ratio of coefficient of consolidation ($c_r\ T_c$) to the coefficient of consolidation, c_r (from Indraratna et al. [4]) ranges between 0.8–1.4 and 0.7–1.4 for different permeability and smear ratios (Table 3).

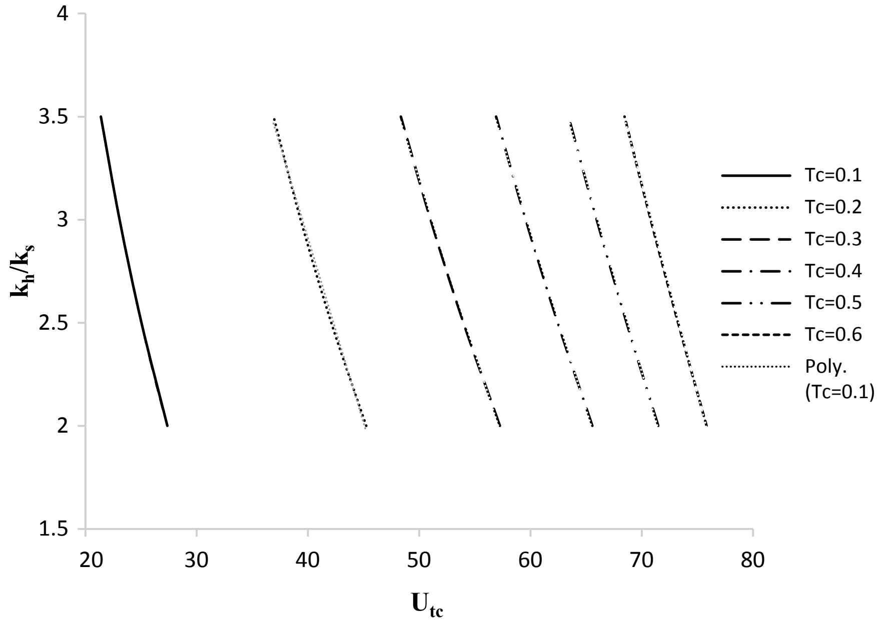

Fig. 9 U_{tc} versus $k_h/k_s$for $n = 20$

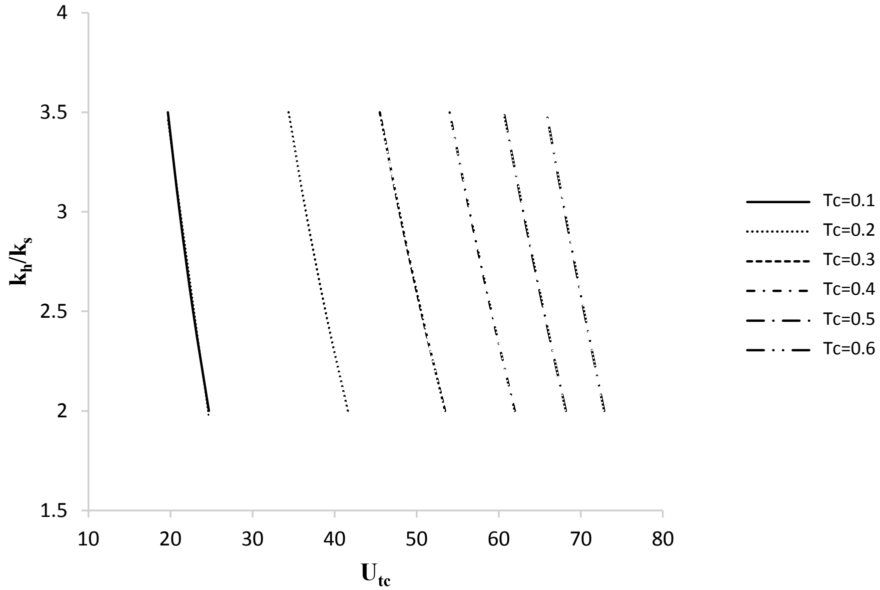

Fig. 10 U_{tc} versus k_h/k_s for $n = 30$

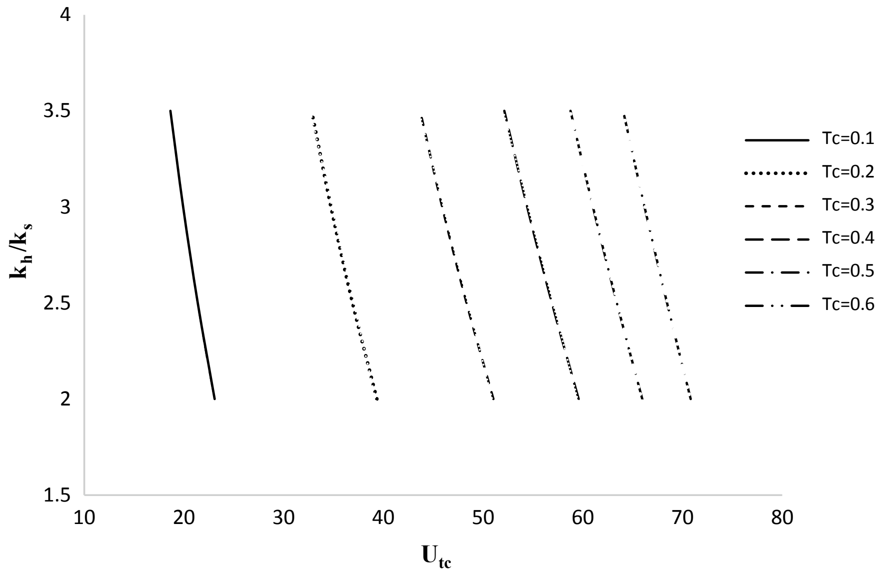

Fig. 11 U_{tc} versus $k_h/k_s$for $n = 40$

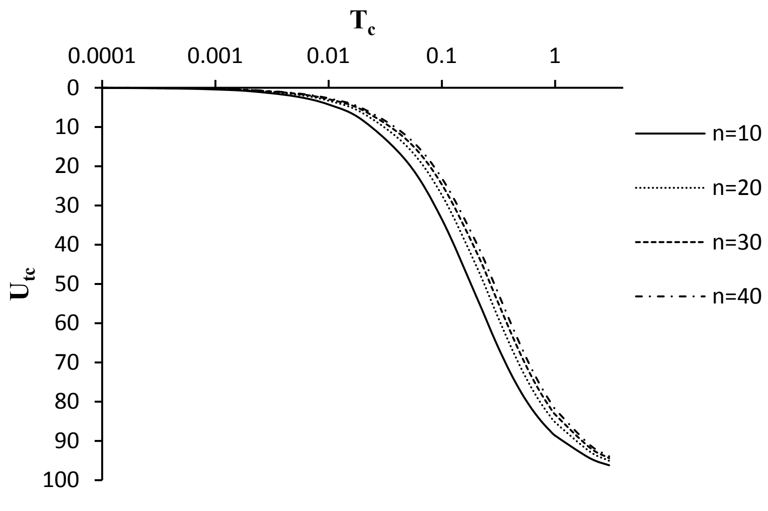

Fig. 12 T_c versus U_{tc} for different 'n' under $k_h/k_s = 2$

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,

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
WD1	0.6	1.6	38	2.1	0.18	2.1	0.19
WD2	1.1		50	2.3	0.32	2.2	0.33
WD3	0.9	1.4	64	2.1	0.38	1.9	0.37
WD4	1.3	2.4	54	2.0	0.27	2.3	0.28
WD5B	0.9	1.6	56	1.8	0.265	1.9	0.265
VC1	0.5	1.2	42	3.0	0.25	2.5	0.24
VC2	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)
WD1	1.16	0.84	0.80	0.80	0.70
WD2	1.31	1.38	1.05	1.42	1.08
WD3	0.89	1.33	1.40	1.30	1.40
WD4	1.02	1.04	1.02	1.08	1.06
WD5B	0.90	0.92	1.03	0.92	1.03
VC1	1.70	2.07	1.20	2.02	1.10
VC2	1.41	1.90	1.30	1.82	1.30

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-documented case history, reported by Indraratna et al. [4]. 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. The coefficients of radial consolidation ($c_r\ T_c$) obtained from both the approaches are close and compare well with those of Indraratna et al. [4].

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