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Geotechnical Properties of Soft Improved Ground from *in-situ* Time-Settlement Plots

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Abstract

Ground improvement using PVDs or sand drains can significantly shorten the time for primary consolidation. In most cases, surcharge load is built over a period of time during which some consolidation occurs. In this study, a method is developed for the estimation of the coefficient of consolidation based on the degree of consolidation at the end of construction time for sand drain treated ground. The proposed method is used for the estimation of coefficient of consolidation for few test cases. Thus, it is possible to estimate the *in situ* coefficient of consolidation at early times from the observed time-settlement plots.

Keywords: Coefficient of consolidation • Sand drains • Asaoka plots

Introduction

Settlement of soft clay consists of immediate, consolidation and creep or secondary settlements. Largest proportion of the settlement of soft clay is attributed to the consolidation process. Because of the very low permeability, the primary consolidation settlement takes a long time to complete [1-3]. Structures constructed on soft soils face problems of stability and serviceability if measures are not taken to improve them. Ground improvement techniques are required to overcome these problems. Ground improvement techniques essentially increase the shear strength and reduce the compressibility of the soil to a desired extent. Pre-fabricated vertical drain technique is one of the most suitable methods to accelerate the dissipation of excess pore pressures. Application of ground improvement method using prefabricated vertical drains (PVD) coupled with surcharge or preloading can significantly shorten the period of primary settlement. PVDs or sand drains greatly shorten the drainage path. A method proposed in the paper involves estimation of the coefficient of consolidation for radial flow from *in situ* time – settlement plots. Queyroi et al. [4] presented the solution for the degree of consolidation, U_r, for radial flow and time-dependent loading for the equal strain case. The degree of consolidation, U_{rt0}, at the end of construction period for no smear (s becomes unity) case is:

$$U_{r(t0)} = 1 - \frac{F(n)}{8T_{R0}}\left[1 - e^{\frac{-8T_{R0}}{F(n)}}\right] \quad (1)$$

Where $T_{R0} = \frac{C_{vr}\,t_0}{4d_e^2}$ - the time factor at the end of construction

$$F(n,s) = F_1(n,s) + \theta F_2(n,s) \quad (2)$$

$$F_1(n,s) = \frac{n^2}{n^2 - s^2}\ln\left(\frac{n}{s}\right) + \frac{s^2 - 3n^2}{4n^2} \quad (3)$$

$$F_2(n,s) = \frac{n^2}{n^2 - s^2}\ln(s) \quad (4)$$

n is the ratio of diameter of unit cell, d_e, to the diameter of the drain, d_w, d_e = 1.128S and 1.05S for drains installed in square and triangular patterns respectively, S – spacing between drains. Smear factor, s is the ratio of radius of smear zone to radius of drain and c_{vr}- the coefficient of consolidation for radial flow.

The degree of consolidation, $U_{r(t0)}$ at the end of construction period is plotted with time factor, T_{R0}, for different values of ‘n (the ratio of unit cell, d_e, to that of drain, d_w) (Figure 1).

Degree of consolidation, $U_{r(t0)}$ increases (Figure 1) with time factor, T_{R0}, corresponding to end of construction but decreases with n. i.e., with larger spacing of the PVDs or sand drains.

Application of Proposed Method

From a given time-settlement plot, the final/ultimate settlement, S_{ult}, is estimated using Asaoka method [2]. The settlement, S_{t0}, at the end of construction time (t_0) is noted from the *in situ* time – settlement data. The degree of consolidation, $U_{r(t0)}$, is

$$U_{r(t0)} = \frac{S_{t0}}{S_{ult}} \quad (5)$$

The time factor, T_{R0}, corresponding to the end of construction, is obtained from Figure 1 from the estimated $U_{r(t0)}$ and the known value of ‘n’. The coefficient of consolidation with radial flow, c_{vr} is then estimated from the known values of t_0, T_{R0} and d_e, as

$$c_{vr} = \frac{T_{R0} \times d_e^2}{t_0} \quad (6)$$

This method is applied to few case studies reported in literature.

Mud flats, South of Iraq

Mud flats, an extension of the deltas of the rivers Tigris and Euphrates exist at the Arabian Gulf in the South of Iraq. The site is underlain by approximately 10 m of soft, sensitive, normally consolidated clay to salty clay containing seems of silt and/or sand. Unit weight of soil is 1.8 g/cm^3 and plasticity index varies from 20 to 28. Initial void ratio is 0.81 and the compression index is 0.346. Three tanks, A, B and C with diameter of 76.2 m were built.

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Sand drains of dia. 0.3 m were installed in triangular pattern with spacing of 2.0 m, 2.25 m and 2.5 m beneath Tanks A, B and C respectively. Ratios, n = d_e/d_w, of diameter of unit cell to diameter of well are 7.0, 7.875 and 8.75 respectively. Observed time versus settlement plots for Tanks-A, B and C are shown in Figures 2, 3 and 4 respectively.

Asaoka plots with 10-day time step are given in Figures 5, 6 and 7 respectively for Tanks A, B and C. Ultimate settlements, S_{ult} for the tanks A, B and C are obtained as 2.7 m, 3.4 m and 2.9 m respectively and the slopes of the lines fitted are 0.934, 0.956 and 0.93. Settlements, S_{t0}, and the times, t_0, at the end of construction are 1.14 m and 110 days, 1.18 m & 150 day and 1.2 m & 100 days. Degrees of consolidation at end of construction are 0.42, 0.35 and .0.41 and the corresponding time factors, T_{R0} are 0.18, 0.16 and 0.2 from (Figure 1). The coefficients of consolidation, cr for radial flow are c_{VT} = 2.63, 2.17 and 5.05 m²/year (Equation 6).

Embankment on soft clay treated with sand drains

A highway embankment was constructed with a height of 6 m and length of 900 m. Strata is very plastic organic clay with a crust approximately 1.0 m thick. The organic compressible soft clay is 10 m thick Profiles PL1 and PL4 represent different types of foundation soils. Sand drains with outer and inner diameters of 0.3 m and 0.1 m respectively were installed in a triangular mesh of 2.0 m spacing at both the sites.

Profile PL1

PL1 profile was instrumented with settlement gauges and piezometers. The ratio, n, of diameter of unit cell, d_e, to diameter, d_w, of well is 7.0. Observed time-settlements at points T1, T2 and T3 are shown in Figure 8. Ultimate settlements estimated from Asaoka plots shown in Figures 9, 10 and 11.

Settlements, S_{t0}, and time t_0, for end of construction, final settlements, S_{ult}, degrees, $U_{r(t0)}$, of consolidation and time factors, T_{R0}, corresponding to end of construction are determined and listed in Table 1 for the three points for Profile PL1.

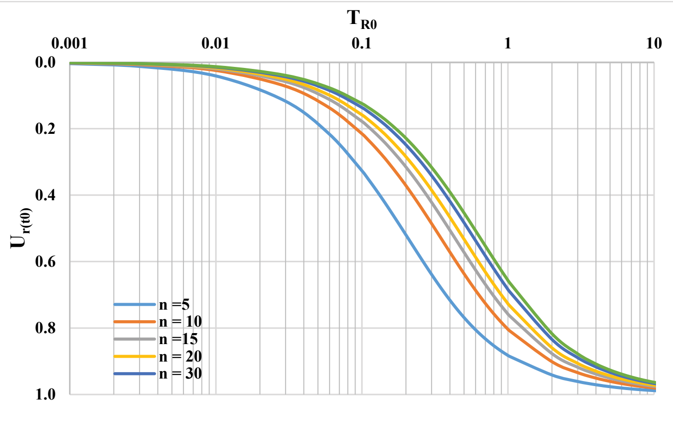

Figure 1. Degree of consolidation, $U_{r(t0)}$ versus Time-factor, T_{R0} for different values of 'n'.

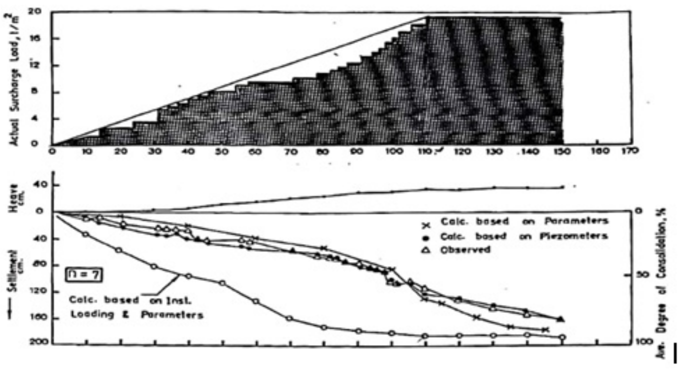

Figure 2. Observed time vs. settlement of Tank-A.

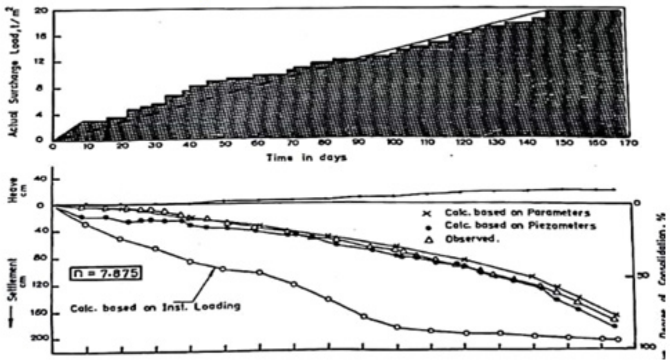

Figure 3. Observed time vs. settlement at Tank-B.

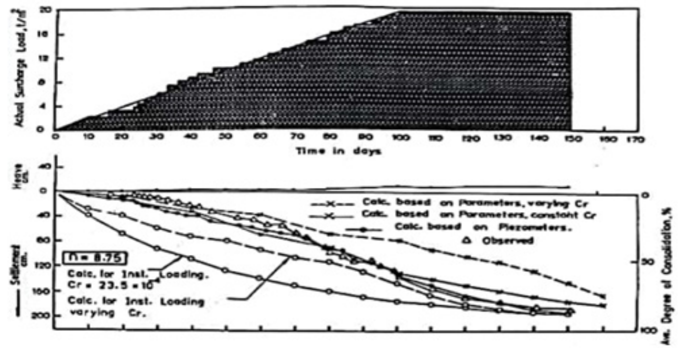

Figure 4. Observed time vs. settlements at Tank-C.

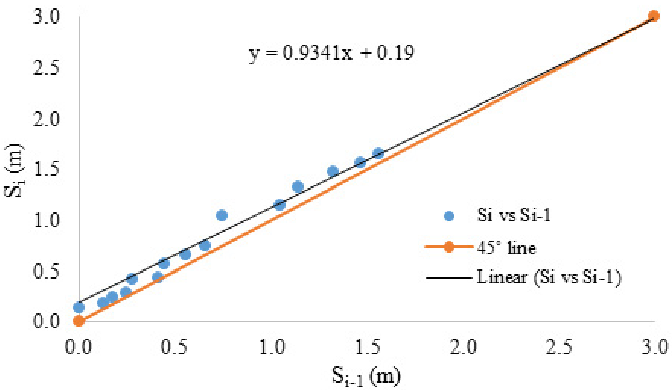

Figure 5. Asaoka plot for Tank-A, Mud flats.

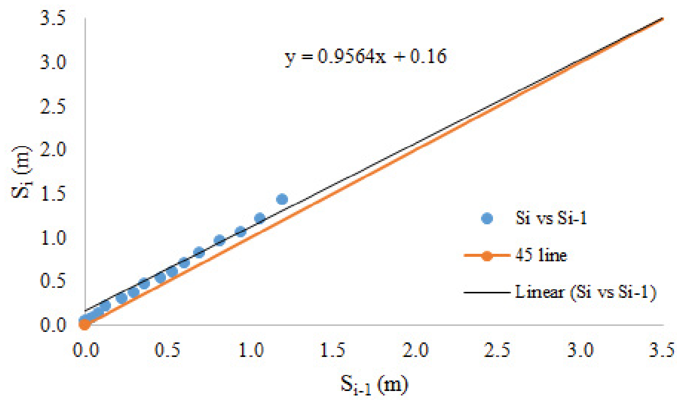

Figure 6. Asaoka plot for Tank- B, Mud flats.

Profile PL4

At PL4, five surface settlement plates are installed at different points on ground. *In situ* time-settlement plots at points T1, T2, T3 and T4 for PL4 profile

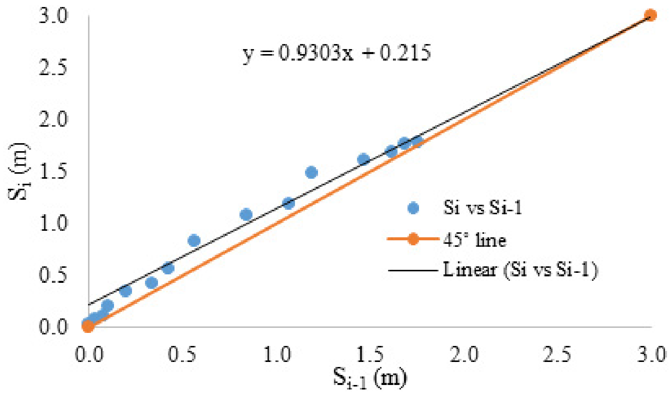

Figure 7. Asaoka plot at Tank-C, Mud flats.

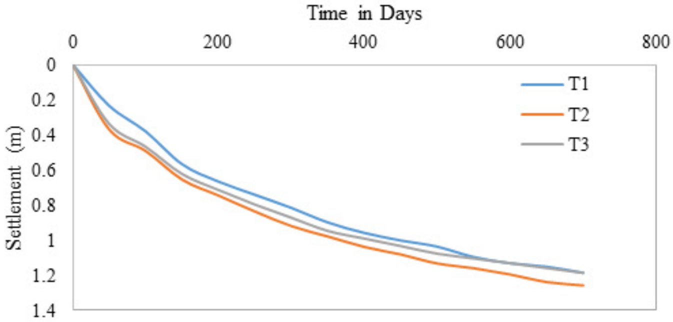

Figure 8. *In-situ* time-settlement plots at PL1 site.

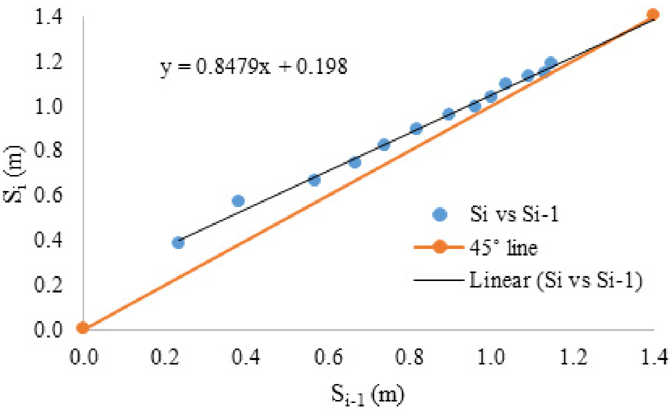

Figure 9. Asaoka plot at T1, Profile PL1.

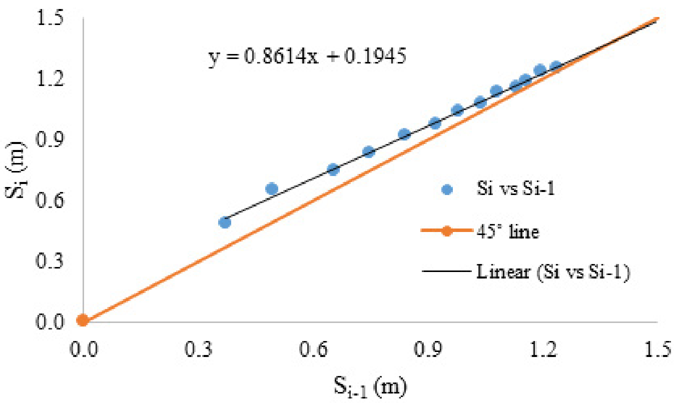

Figure 10. Asaoka plot at T2, Profile PL1.

are shown in Figure 12. Ultimate settlements, S_{ult} estimated using the Asaoka plots for the time-settlement curves for various points T1, T2, T3 and T4 are presented in Figures 13-16.

Diameter of unit cell (d_e) =2.1 m, diameter of well (d_w) is 0.3 m. ratio, n, of diameter of drain to diameter of well) is 7.0, F (n) is 1.598, time interval, ∆t, to draw S_i Vs S_{i-1} plot, is 50 days. Parameters for Profile PL4are tabulated in Table 2. Coefficients of consolidation for radial flow, c_{vr} are estimated by substituting the appropriate parameters in Equation 6, and listed in Table 3 for the two profiles PL1 and PL4.

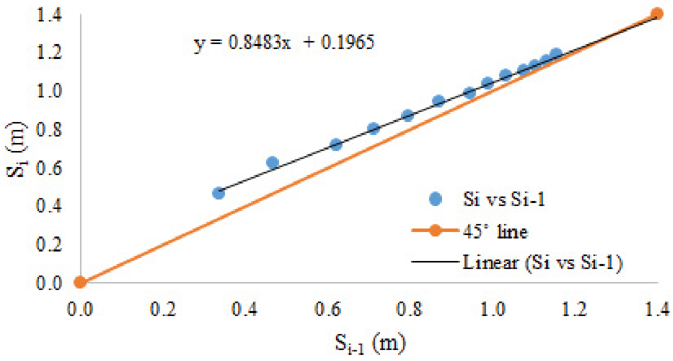

Figure 11. Asaoka plot at t T3, Profile PL1.

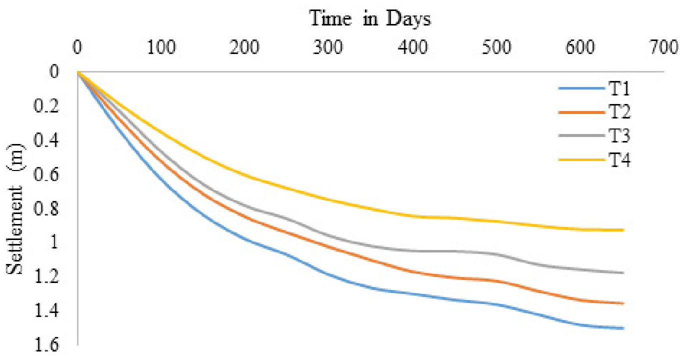

Figure 12. Observed *in-situ* Time-settlement plots at PL4.

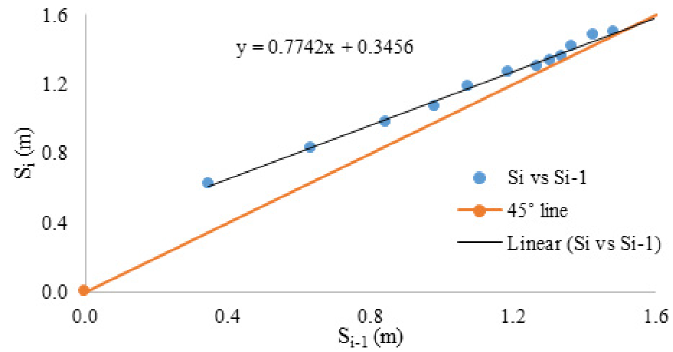

Figure 13. Asaoka plot at point T1 of profile PL4.

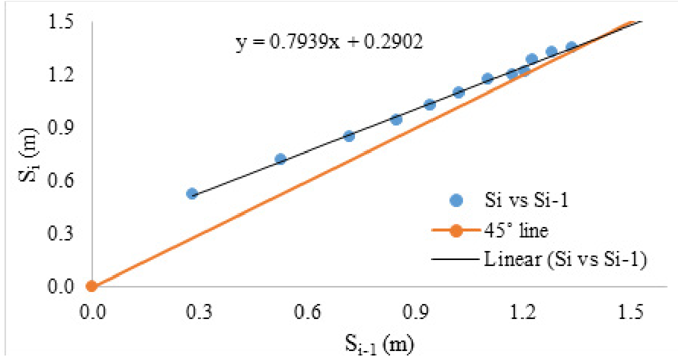

Figure 14. Asaoka plot at point T2 of profile PL4.

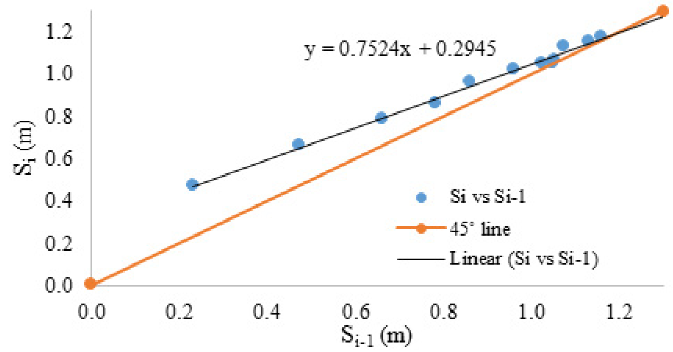

Figure 15. Asaoka plot at point T3 of Profile PL4.

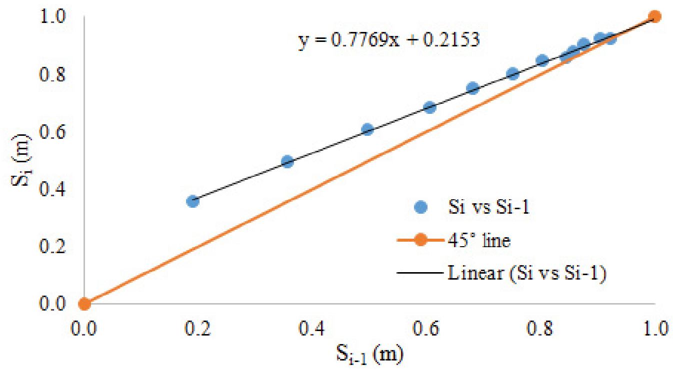

Figure 16. Asaoka plot at point T4 of profile PL4.

Table 1. Parameters for Profile PL1.

Profile	S_{t0} (m)	t_0 (days)	S_{ult}(m)	$U_{r(to)}$	T_{R0}
T1	1.053	500	1.3	0.81	0.8
T2	1.084	500	1.4	0.775	0.68
T3	1.132	500	1.3	0.871	1.25

Table 2. Parameters of Profile PL4.

Depth(m)	S_{t0} (m)	t_0 (days)	S_{ult} (m)	$U_{r(t0)}$	T_{R0}
T1	1.364	500	1.50	0.909	1.80
T2	1.226	500	1.36	0.901	1.75
T3	1.071	500	1.16	0.923	2.05
T4	0.868	500	0.96	0.904	1.60

Results and Discussion

For the site of Mud flats the range of coefficients of consolidation for radial

Table 3. c_{vr} for Profiles PL1 and PL4.

Profile PL1		Profile PL4	
Point	**c_{vr} (m²/yr.)**	**Point**	**c_{vr} (m²/yr.)**
T1	2.58	T1	5.79
T2	2.19	T2	5.63
T3	4.02	T3	6.60
		T4	5.15

flow (c_{vr}) from the laboratory test results is from 0.95 to 9.47 m²/year [3] while the range of *in situ* coefficients of consolidation for radial flow (c_{vr}) estimated using the proposed degree of consolidation at end of construction is between 2.63 to 5.05 m²/year, very different from the laboratory determined values.

For the site of treated ground at profiles PL1 and PL4 the range of laboratory coefficients of consolidation is between 4.73 to 37.87 m²/year [4] while the estimated *in situ* coefficients of consolidation for radial flow by the proposed new approach, i.e., based on degree of consolidation at the end of construction time, is in the range 2.19 to 4.02 m²/year for profile PL1 and 5.15 to 6.60 m²/year for profile PL4. Once again the *in situ* coefficients are very different from the laboratory determined values. The behaviour of the ground is very different from that determined in the laboratory based on small size samples.

Conclusion

PVDs or Sand drains with surcharge helps in accelerating the consolidation process *in situ*. The proposed method estimates the coefficient of consolidation for radial flow from *in-situ* time-settlement plots at early times. The results estimated from *in situ* time – settlement plot are different from laboratory determined values.

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