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Improved Design Procedures for Ground Improvement using Pre- Fabricated Vertical Drains

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Abstract

Background/Objective: Ground improvement for soft saturated clay soil is often achieved by preloading combined with vertical drains. Use of vertical drains gives rise to smear zone and well resistance, which hinders consolidation. However, Indian code of practices doesn't consider this aspect. **Method:** Computation of optimum spacing for vertical drains is iterative and tedious procedure. Therefore, an automate procedure using goal seek function of MS Excel is developed which gives optimum spacing instantly. Using developed spreadsheet, effect of smear zone has been studied by comparing field data to that obtained by using theoretical equations. **Findings:** Time estimates for target value of consolidation required in a project are better predicted by considering smear effects. Based on these findings it has been suggested to incorporate the effect of smear zone in Indian Codes for rational design of PVD. **Application/Improvement:** Using proposed modifications in Indian code of practices realistic estimate for desired consolidation can be found quickly.

Keywords: Code of Practices, Optimum Design, PVDs, Radial Consolidation, Smear Zone

1. Introduction

Different parts of country consist of soft saturated clay and very soft marine clay generally close to coastal areas, which make construction activities difficult. Therefore, it becomes necessary to use ground improvement techniques to facilitate construction in shortest time possible. Various ground improvement techniques used to stabilize clayey soils include stone columns, sand drains, stabilization using additives[1–3]. One of the major techniques being used these days is pre-fabricated vertical drains in conjunction with preloading and preloading along with vacuum.

One of the main considerations while constructing structures on soft, highly compressible, normally consolidated clayey soil layers, is the settlements which are expected as the result of the loads. The permeability of the clayey soil is very low so the dissipation of pore pressure takes time. Time can be minimized by installation of vertical drains or wick drains. The time required mainly depends on permeability of soil and drainage path[4]. The time can be reduced appreciably if the drainage path is shortened by means of vertical drains[4]. Therefore, vertical drains can reduce settlements from years to months and hence most settlement occurs during construction period, and magnitude of post-construction settlements is minimized. Other than expediting settlement wick drains find wide range of applications in as in to reduce potential drag on piles, waste and contaminant sites and collection of polluted groundwater. Now days the use of prefabricated vertical drains (PVD) are increasingly becoming popular. Various case studies have demonstrated the use of PVD's in India[5–7].

2. Mathematical Representation of Water Flow in Soil and PVDs

Partial differential equation for axisymmetric water flow in soil is given as follows:

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

Where,

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C_r = consolidation coefficient in radial (horizontal) direction

C_v = consolidation coefficient in vertical direction

r = Distance (radial)

u = pore pressure at distance r

t = time

Consolidation due to vertical flow can be calculated as follows[8]:

$$U_{vr} = 1 - (1 - U_v)(1 - U_r) \quad (2)$$

Consolidation due to vertical flow can be calculated as follows[9]:

$$U_v = 1 - \sum_{m=0}^{\infty} \frac{2}{M^2} e^{-M^2 T_v} \quad (3)$$

Where:

$$M = \frac{(2m + 1)\pi}{2} \quad (4)$$

$$T_v = \frac{c_v t}{H2} \quad (5)$$

C_v= coefficient of vertical consolidation

H= Drainage distance due to vertical flow

Average degree of consolidation in radial direction for sand drains[10] is given by:

$$U_r r = 1 - \exp(-(8\, T_r r)/(F(N_D D)) \quad) \quad (6)$$

$$F(N_D) = \frac{N^2}{N^2 - 1} \ln(N_D) - \frac{3N^2 - 1}{4N^2} \quad (7)$$

where,

U_r = average degree of consolidation in radial direction

N_D = diameter ratio (i.e. $N_D = d_e/d_c$)

d_e = Equivalent diameter (unit cell)

d_c = Diameter (sand drain)

T_r= time factor due to radial flow

$=c_r t/d_c^2$ (8)

However, during installation of vertical drains nearby soil structure is disturbed close to mandrel. Driven sand drains are not feasible in soft and sensitive clays as the former leads to reduction in shear strength and permeablity[11]. In the disturbed zone, an increase in pore pressure, strength and water content decrease is observed along with reduction of hydraulic conductivity compared to initial values before PVD' installation[12]. Consequently, flow of water is slowed down and consolidation gets delayed. Therefore, effect of smear should be considered in calculation of degree of consolidation.

Average degree of consolidation of a sand drain due to radial flow considering smear and well resistance[13]:

$$U_r = 1 - \exp\left[\frac{-8T_r}{F_m(N)}\right] \quad (9)$$

$$F_m = \frac{\ln N_D}{N_s} + \frac{k_r}{k_s} lnN_s - \frac{3}{4} + \frac{\pi z(2h_{dr} - z)k_r}{Q_c} \quad (10)$$

$$F_m = \frac{\ln N_D}{N_s} + \frac{k_r}{k_s} lnN_s - \frac{3}{4} + \frac{\pi z(2h_{dr} - z)k_r}{Q_c}$$

Where,

N_s= Diameter ratio (smeared zone to vertical drain) (i.e. $N_s = d_s/d_c$)

k_r = Radial permeability (undisturbed surrounding soil)

k_s = radial permeability (smeared soil)

z = depth in ground at which degree of consolidation is to be computed

h_{dr} = Longest drainage path in vertical flow

Q_c = discharge capacity of a vertical drain

$=\frac{k_c \pi d_c^2}{4}$

K_c = vertical permeability of drain well

In theoretical approach for horizontal drainage[14–19], there is consensus between effects of smear and spacing also and effect of well resistance is also comparable among the solutions only exception being the approximate solution by Hansbo. Model suggested by Hansbo is still useful for practical purposes because of its simplicity[20–23]. Canadian Foundation manual[24] also recommended Hansbo[15] model.

For PVD, equivalent diameter is given by:

$$d_e = \frac{2(a + b)}{\pi} \quad (12)$$

where,

a = width (band- shaped drain cross section)

b = thickness (band- shaped drain cross section)

3. Optimum Spacing of PVDs Using Goal Seek Function in MS Excel

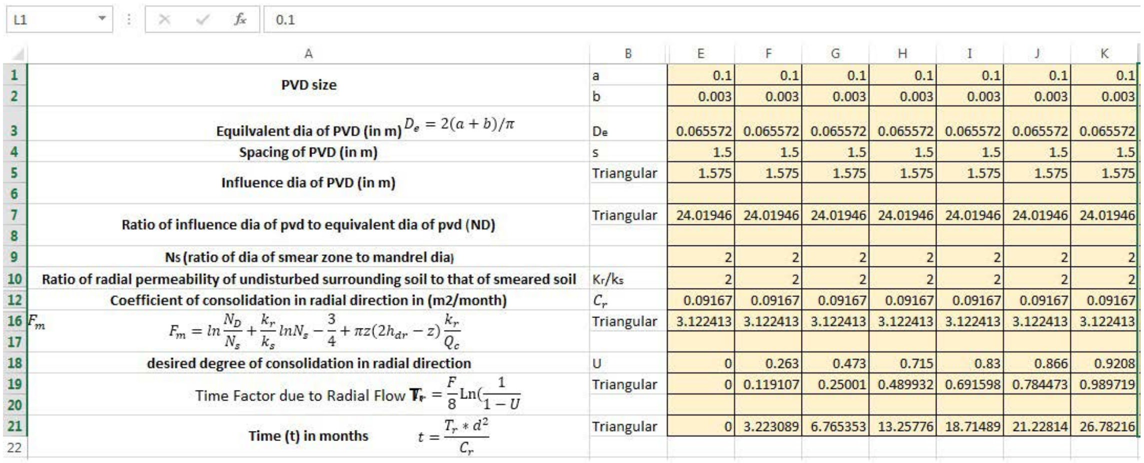
Using data of a field study attempt has been made to demonstrate the effect of smear zone in computation of consolidation.

Data:

Time available: 18 months

$k_r/k_s = 2$

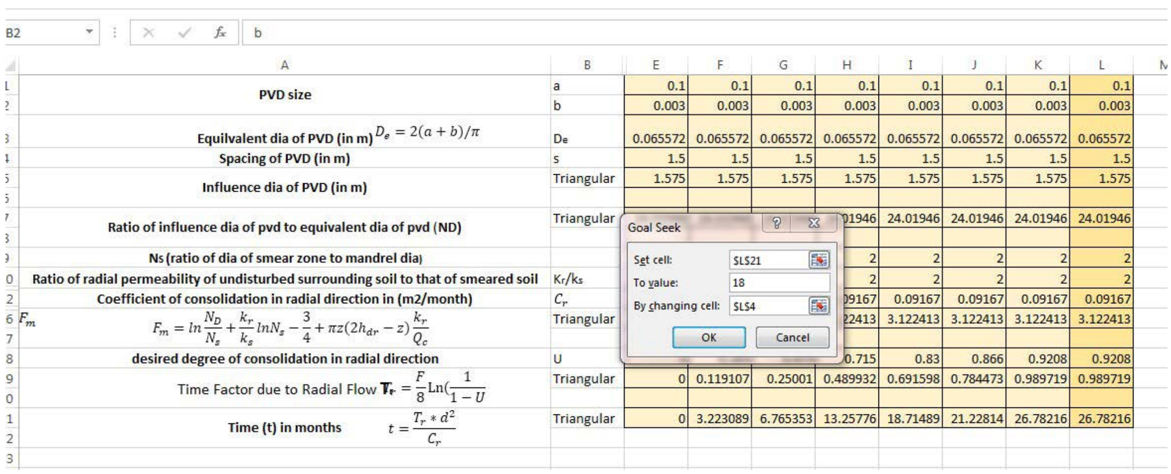
$N_s = 2$



L1 | 0.1

	A	B	E	F	G	H	I	J	K
1	PVD size	a	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2		b	0.003	0.003	0.003	0.003	0.003	0.003	0.003
3	Equivalent dia of PVD (in m) $D_e = 2(a+b)/\pi$	De	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572
4	Spacing of PVD (in m)	s	1.5	1.5	1.5	1.5	1.5	1.5	1.5
5	Influence dia of PVD (in m)	Triangular	1.575	1.575	1.575	1.575	1.575	1.575	1.575
6									
7	Ratio of influence dia of pvd to equivalent dia of pvd (ND)	Triangular	24.01946	24.01946	24.01946	24.01946	24.01946	24.01946	24.01946
8									
9	Ns (ratio of dia of smear zone to mandrel dia)		2	2	2	2	2	2	2
10	Ratio of radial permeability of undisturbed surrounding soil to that of smeared soil	Kr/Ks	2	2	2	2	2	2	2
12	Coefficient of consolidation in radial direction in (m2/month)	C_r	0.09167	0.09167	0.09167	0.09167	0.09167	0.09167	0.09167
16	F_m $F_m = ln\frac{N_D}{N_s} + \frac{k_r}{k_s} lnN_s - \frac{3}{4} + \pi z(2h_{dr} - z)\frac{k_r}{Q_c}$	Triangular	3.122413	3.122413	3.122413	3.122413	3.122413	3.122413	3.122413
17									
18	desired degree of consolidation in radial direction	U	0	0.263	0.473	0.715	0.83	0.866	0.9208
19	Time Factor due to Radial Flow $T_r = \frac{F}{8}\mathrm{Ln}(\frac{1}{1-U}$	Triangular	0	0.119107	0.25001	0.489932	0.691598	0.784473	0.989719
20									
21	Time (t) in months $t = \frac{T_r * d^2}{C_r}$	Triangular	0	3.223089	6.765353	13.25776	18.71489	21.22814	26.78216
22									

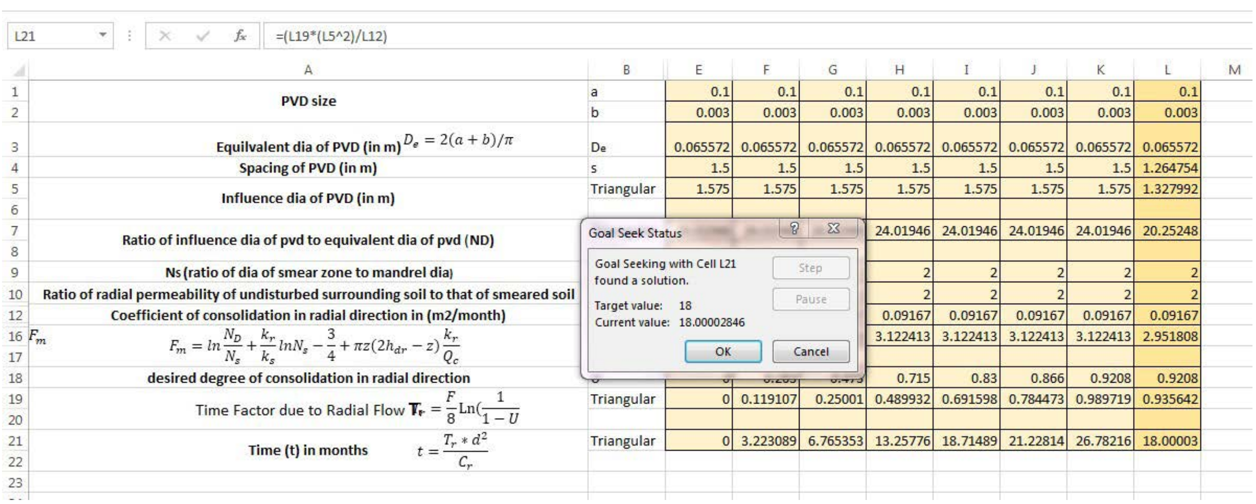
Figure 1. Time required to achieve given degree of consolidation based on data in the research paper.



B2 | b

	A	B	E	F	G	H	I	J	K	L
1	PVD size	a	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2		b	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
3	Equivalent dia of PVD (in m) $D_e = 2(a+b)/\pi$	De	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572
4	Spacing of PVD (in m)	s	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
5	Influence dia of PVD (in m)	Triangular	1.575	1.575	1.575	1.575	1.575	1.575	1.575	1.575
6										
7	Ratio of influence dia of pvd to equivalent dia of pvd (ND)	Triangular				01946	24.01946	24.01946	24.01946	24.01946
8										
9	Ns (ratio of dia of smear zone to mandrel dia)					2	2	2	2	2
10	Ratio of radial permeability of undisturbed surrounding soil to that of smeared soil	Kr/Ks				2	2	2	2	2
12	Coefficient of consolidation in radial direction in (m2/month)	C_r				09167	0.09167	0.09167	0.09167	0.09167
16	F_m $F_m = ln\frac{N_D}{N_s} + \frac{k_r}{k_s} lnN_s - \frac{3}{4} + \pi z(2h_{dr} - z)\frac{k_r}{Q_c}$	Triangular				22413	3.122413	3.122413	3.122413	3.122413
17										
18	desired degree of consolidation in radial direction	U				0.715	0.83	0.866	0.9208	0.9208
19	Time Factor due to Radial Flow $T_r = \frac{F}{8}\mathrm{Ln}(\frac{1}{1-U}$	Triangular	0	0.119107	0.25001	0.489932	0.691598	0.784473	0.989719	0.989719
20										
21	Time (t) in months $t = \frac{T_r * d^2}{C_r}$	Triangular	0	3.223089	6.765353	13.25776	18.71489	21.22814	26.78216	26.78216
22										
23										

Figure 2. Use of goal seek function to find optimal spacing to achieve 90% degree of consolidation.



L21 | =(L19*(L5^2)/L12)

	A	B	E	F	G	H	I	J	K	L
1	PVD size	a	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
2		b	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
3	Equivalent dia of PVD (in m) $D_e = 2(a+b)/\pi$	De	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572	0.065572
4	Spacing of PVD (in m)	s	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.264754
5	Influence dia of PVD (in m)	Triangular	1.575	1.575	1.575	1.575	1.575	1.575	1.575	1.327992
6										
7	Ratio of influence dia of pvd to equivalent dia of pvd (ND)					24.01946	24.01946	24.01946	24.01946	20.25248
8										
9	Ns (ratio of dia of smear zone to mandrel dia)					2	2	2	2	2
10	Ratio of radial permeability of undisturbed surrounding soil to that of smeared soil					2	2	2	2	2
12	Coefficient of consolidation in radial direction in (m2/month)					0.09167	0.09167	0.09167	0.09167	0.09167
16	F_m $F_m = ln\frac{N_D}{N_s} + \frac{k_r}{k_s} lnN_s - \frac{3}{4} + \pi z(2h_{dr} - z)\frac{k_r}{Q_c}$					3.122413	3.122413	3.122413	3.122413	2.951808
17										
18	desired degree of consolidation in radial direction					0.715	0.83	0.866	0.9208	0.9208
19	Time Factor due to Radial Flow $T_r = \frac{F}{8}\mathrm{Ln}(\frac{1}{1-U}$	Triangular	0	0.119107	0.25001	0.489932	0.691598	0.784473	0.989719	0.935642
20										
21	Time (t) in months $t = \frac{T_r * d^2}{C_r}$	Triangular	0	3.223089	6.765353	13.25776	18.71489	21.22814	26.78216	18.00003
22										
23										

Figure 3. Optimal spacing calculated by goal seek function.

Table 1. Comparison of time required to achieve given degree of consolidation

Degree of Consolidation	Time Required in months (smear effect Self)	Time Required in months (without smear effect self)	Time Observed in months (in field)	% Error with smear effect	% Error without smear effect
26.1	3.22	2.51	3	7.44	-16.21
47.3	6.76	5.28	6	12.76	-12.06
71.5	13.26	10.34	12	10.48	-13.84
83.0	18.71	14.59	18	3.97	-18.91
86.6	21.23	16.55	24	-11.55	-31.02
92.08	26.78	20.89	48	-44.20	-56.48

$C_r = 1.1\ m^2/yr$

Size of band drains: 100mm x 3mm

4. Results

Following Tables compare the time and spacing needed for achieving desired degree of consolidation when effect of smear zone is considered and when it is not considered to that of time taken in actual conditions. It can be seen from the tables that Hansbo's model gives accurate results till degree of consolidation is less than 80%. This can be attributed to the fact that consolidation is dependent on geotechnical properties and parameters which are altered considerably in the later stages of consolidation

Table 2. Comparison of optimal spacing to achieve 90% degree of consolidation in 18 months

Spacing Required (smear effect)	**1.265 m**
Spacing Required (without smear effect)	1.41 m

5. Conclusions

While many authors have attempted successfully to quantify the effect of smear zone but Hansbo's model[13,15] is still widely used because of its simplicity. Calculating consolidation due to vertical drains without considering the effect of smear zone gives non-conservative values. This may prove to be detrimental for the structures as they become prone to differential settlement. Further based on data of a case study of KandlaPort[6] effect of smear effect was analysed which was in accordance with the fact that considering the effect of smear zone gives conservative values. Based on the above verification it is suggested that Indian Codes[4] should incorporate the effect of smear zone.

This paper presents the smear zone effect on degree of consolidation in pre-fabricated vertical drains. While many authors have attempted successfully to quantify the effect of smear zone but Hansbo's model is still widely used because of its simplicity. Well resistance effect is considered negligible for most cases as PVD's designed provide no resistance to water flow. Accurate prediction of consolidation depends majorly on the precision of geotechnical properties and parameters of soil established by field and laboratory tests. Calculating consolidation due to vertical drains without considering the effect of smear zone gives non-conservative values. This may prove to be detrimental for the structures as they become prone to differential settlement. Further based on data of a case study of Kandla Port[18] effect of smear effect was analysed which was in accordance with the fact that considering the effect of smear zone gives conservative values. Based on the above verification it is suggested that Indian Codes[19] should incorporate the effect of smear zone.

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