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Empirical Analysis of Partially Penetrated Prefabricated Vertical Drains (PVD) on Acceleration Consolidation of Soft Soil

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Abstract: The soft soil problem is one of the problems that must be resolved before construction begins. One way to solve this problem is to use prefabricated vertical drains (PVD), which works by cutting the drainage path into shorter lengths, thereby speeding up the consolidation rate. In this research, an empirical analysis of the use of PVD will be calculated to determine the effective depth of PVD. The analysis will be calculated using Hansbo's theory and Terzaghi's one-dimensional consolidation. Depth variations are considered from 100%, 90%, 80%, 70%, 60%, and 50% of the compressible soil depth. The analysis results show that in 180 days a consolidation degree of 90% has been achieved at variations of 90% and 100% of the depth of the compressible soil. Meanwhile, within 180 days, primary consolidation residue values <0.3 m occurred with variations of 70%-100%. It can be said that the depth of PVD installation can be reduced by 70% -90% of the depth of compressible soil.

Keywords: Soft Soil Consolidation, PVD, Effective Depth

Introduction

Construction will continue to develop as time goes by and the population increases. One aspect that needs to be considered in construction is the geotechnical aspect which specifically discusses the properties and behavior of soil (Ngo, 2024; Nguyen, 2024). Soil materials have different properties and characteristics (Ghose, 2024; Liu, 2024). It is not uncommon to find various problematic soils in the field, one of which is soft soil which needs further attention. Soft soil has the characteristics of low shear strength, low bearing capacity, consolidation that lasts for a long time, and high compressibility (Das, 1995). One effective way to improve soil is preloading with vertical drainage (Indraratna et al., 2003). Vertical drainage has a working system, namely by cutting the drainage path so that it can reduce consolidation time to be faster, assisted by the embankment above it (Hansbo, 2015).

One aspect that should be considered before construction is carried out is the depth of PVD installation (de Almeida, 2023; Nguyen, 2023a). In certain cases, the installation process does not need to be installed fully penetrated into the compressible soil to correct problems with soil consolidation and shear strength (FHWA, 1986). This research will further analyze the effectiveness of PVD installation depth. The analysis was carried out using empirical analysis calculated using Hansbo's theory (1979) for layers installed with PVD (improved layer) and one-dimensional consolidation theory by Terzaghi for soil without PVD (unimproved layer).

The effectiveness of PVD installation depth can be interpreted as the minimum possible depth used during the installation process (Huang, 2023; Lei, 2023; Wu, 2023). Determining the criteria for soil effectiveness can be seen in terms of the degree of consolidation or primary consolidation residue that occurs (Kanungo, 2023; Nguyen, 2023b; Sari, 2023). Ong et al. (2012) states that the effective depth is determined in the condition that after 6 months of loading, the average degree of consolidation has reached 90% or the residual value of primary consolidation is less than 0.3 m (Bergado, 2022; Mridakh, 2022; Ni, 2022; Sun, 2022).

Methodology

The method used in this research is an empirical approach using (Hansbo, 1979) and Terzaghi's theory (Hardiyatmo, 2018). The soil data used is dominated by clay with various consistencies. Based on the test data, it was found that soil with an N-SPT value < 10 was at a depth of 20 m. The soil data parameters used can be seen in Table 1 as follows.

Table 1. Soil parameter

Symbol	Parameter	Unit	UDS 1 (0,00 – 6,00 m)	UDS 2 (6,00 – 20,00 m)
E	Effective E-Modulus	kPa	3148,5409	2330,5778
γ	Unit Weight	kN/m³	12,90	13,14
Gs	Spesific gravity	-	2,67	2,68
e	Void ratio	-	2,03	1,87
c	Cohesion	kg/cm²	0,013	0,063
φ	Phi	°	5,83	5,82
v	Poisson's ratio	-	0,3246	0,3406
w	Saturated WC	%	46,09%	40,68%
mv	Compressibility	cm²/kg	0,0474	0,0577
kx	Saturated kx	m/s	9,2880E-08	9,9537E-08
ky/kx	Anisotropy kx/ky ratio	-	1/1	1/1
Cc	Compression index	-	0,9447	0,9952
Cr	Recompression index	-	0,0579	0,0437
Cv	Coefficient of consolidatiion	cm²/s	0,0019	0,0017
Mv	Coefficient of volume change	cm²/kg	0,0474	0,0577

Table 1 above is data that will be used in empirical calculations. The conversion and correlation of test data to the data required in this research refers to Ameratunga et al. (2016)

Data parameters for the embanked soil and sand drained used in this research can be seen in Table 2 as follows.

Table 2. Preloading parameter

Symbol	Parameter	Unit	Preloading	Sand drained
E	Effective E-Modulus	kPa	20000	20000
γ	Unit Weight	kN/m³	18,00	18,00
v	Poisson's ratio	-	0,4900	0,3340
φ	Phi	°	30	30
c	Cohesion	kN/m²	0	0

Table 3 above is data on specifications for embankment and drained sand which will be used in empirical calculations. This parameter is an assumption from general embankment

soil in the field which is granular soil. Preloading will be piled up to a height of 5 meters including sand drained as high as 0.5 m from the ground surface.
The PVD data parameters used in this research can be seen in Table 3 as follows.

Table 3. PVD parameter

Symbol	Parameter	Unit	PVD
a	Width	mm	100
b	Length	mm	3
E	Effective E-Modulus	kPa	3000
γ	Unit Weight	kN/m³	18,00
v	Poisson's ratio	-	0,333
w	Saturated WC	%	43,39%
mv	Compressibility	cm²/kg	0,0546
kx	Saturated kx	m/s	9,6208E-08
ky/kx	Anisotropy kx/ky ratio	-	1/1

Table 3 above is the PVD specification data that will be used in empirical calculations. PVD will be analyzed with an installation distance of 1 m and a square installation pattern. The installation depth will be varied as deep as 100%, 90%, 80%, 70%, 60% and 50% of the depth of the compressible soil.

Result and Discussion

The results of the empirical analysis are the degree of consolidation and the consolidation value. Based on these results, it will be observed on the 180th day what the value of each variation is as follows.

Depth Variation: 100%

The results of the analysis at 100% depth variation can be seen in Table 4 as follows

Table 4. Empirical analysis result for 100% depth variation

Layer With PVD				*Layer Without PVD*			
U_1%	t (day)	S_c (m)	$S_{c\ residu}$ (m)	U_2%	t (day)	S_c (m)	$S_{c\ residu}$ (m)
0%	0,00	0,0000	0,8570	0%	0	0	0,0000
5%	2,06	0,0428	0,8141	5%	0	0	0,0000
10%	4,12	0,0857	0,7713	10%	0	0	0,0000
15%	6,43	0,1285	0,7284	15%	0	0	0,0000
20%	8,94	0,1714	0,6856	20%	0	0	0,0000
25%	11,65	0,2142	0,6427	25%	0	0	0,0000
30%	14,52	0,2571	0,5999	30%	0	0	0,0000
35%	17,70	0,2999	0,5570	35%	0	0	0,0000
40%	20,94	0,3428	0,5142	40%	0	0	0,0000

Layer With PVD				*Layer Without PVD*			
U_1%	t (day)	S_c (m)	$S_{c\ residu}$ (m)	U_2%	t (day)	S_c (m)	$S_{c\ residu}$ (m)
45%	24,73	0,3856	0,4713	45%	0	0	0,0000
50%	28,83	0,4285	0,4285	50%	0	0	0,0000
55%	32,97	0,4713	0,3856	55%	0	0	0,0000
60%	38,00	0,5142	0,3428	60%	0	0	0,0000
65%	43,63	0,5570	0,2999	65%	0	0	0,0000
70%	50,62	0,5999	0,2571	70%	0	0	0,0000
75%	58,17	0,6427	0,2142	75%	0	0	0,0000
80%	67,82	0,6856	0,1714	80%	0	0	0,0000
85%	79,88	0,7284	0,1285	85%	0	0	0,0000
90%	95,59	0,7713	0,0857	90%	0	0	0,0000
95%	**125,59**	**0,8141**	**0,0428**	95%	0	0	0,0000
99%	**196,73**	**0,8484**	**0,0086**	99%	0	0	0,0000

Depth Variation: 90%

The results of the analysis at 90% depth variation can be seen in Table 5 as follows

Table 5. Empirical analysis result for 90% depth variation

Layer With PVD				*Layer Without PVD*			
U_1%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)	U_2%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)
0%	0,00	0,0000	0,7592	0%	0,00	0,0000	0,0978
5%	2,00	0,0380	0,7212	5%	0,51	0,0049	0,0929
10%	3,99	0,0759	0,6833	10%	2,05	0,0098	0,0880
15%	6,22	0,1139	0,6453	15%	4,62	0,0147	0,0831
20%	8,67	0,1518	0,6073	20%	8,21	0,0196	0,0782
25%	11,29	0,1898	0,5694	25%	12,83	0,0244	0,0733
30%	14,11	0,2278	0,5314	30%	18,47	0,0293	0,0685
35%	17,19	0,2657	0,4935	35%	25,14	0,0342	0,0636
40%	20,39	0,3037	0,4555	40%	32,84	0,0391	0,0587
45%	24,07	0,3416	0,4176	45%	41,56	0,0440	0,0538
50%	28,06	0,3796	0,3796	50%	51,31	0,0489	0,0489
55%	32,17	0,4176	0,3416	55%	62,09	0,0538	0,0440
60%	37 ,10	0,4555	0,3037	60%	73,89	0,0587	0,0391
65%	42,61	0,4935	0,2657	65%	88,96	0,0636	0,0342
70%	49,37	0,5314	0,2278	70%	105,28	0,0685	0,0293
75%	56,82	0,5694	0,1898	75%	124,59	0,0733	0,0244
80%	66,26	0,6073	0,1518	80%	148,22	0,0782	0,0196
85%	78,14	0,6453	0,1139	**85%**	**178,68**	**0,0831**	**0,0147**
90%	95,60	0,6833	0,0759	**90%**	**221,62**	**0,0880**	**0,0098**
95%	**124,86**	**0,7212**	**0,0380**	95%	295,02	0,0929	0,0049
99%	**193,08**	**0,7516**	**0,0076**	99%	465,45	0,0968	0,0010

Depth Variation: 80%

The results of the analysis at 80% depth variation can be seen in Table 6 as follows

Table 6. Empirical analysis result for 80% depth variation

Layer With PVD				*Layer Without PVD*			
U_1%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)	U_2%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)
0%	0,00	0,0000	0,6614	0%	0,0000	0,0000	0,1956
5%	1,93	0,0331	0,6283	5%	2,0526	0,0098	0,1858
10%	3,87	0,0661	0,5953	10%	8,2103	0,0196	0,1760
15%	6,00	0,0992	0,5622	15%	18,4731	0,0293	0,1662
20%	8,41	0,1323	0,5291	20%	32,8411	0,0391	0,1565
25%	10,94	0,1653	0,4960	25%	51,3143	0,0489	0,1467
30%	13,71	0,1984	0,4630	30%	73,8925	0,0587	0,1369
35%	16,69	0,2315	0,4299	35%	100,5759	0,0685	0,1271
40%	19,85	0,2646	0,3968	40%	131,3645	0,0782	0,1173
45%	23,43	0,2976	0,3638	**45%**	**166,2582**	**0,0880**	**0,1076**
50%	27,31	0,3307	0,3307	**50%**	**205,2570**	**0,0978**	**0,0978**
55%	31,39	0,3638	0,2976	55%	248,3610	0,1076	0,0880
60%	36,21	0,3968	0,2646	60%	295,5701	0,1173	0,0782
65%	41,62	0,4299	0,2315	65%	355,8262	0,1271	0,0685
70%	48,15	0,4630	0,1984	70%	421,1212	0,1369	0,0587
75%	55,51	0,4960	0,1653	75%	498,3487	0,1467	0,0489
80%	64,73	0,5291	0,1323	80%	592,8676	0,1565	0,0391
85%	76,43	0,5622	0,0992	85%	714,7236	0,1662	0,0293
90%	93,33	0,5953	0,0661	90%	886,4699	0,1760	0,0196
95%	**121,97**	**0,6283**	**0,0331**	95%	1180,0723	0,1858	0,0098
99%	**188,62**	**0,6548**	**0,0066**	99%	1861,7959	0,1936	0,0020

Depth Variation: 70%

The results of the analysis at 70% depth variation can be seen in Table 7 as follows

Table 7. Empirical analysis result for 70% depth variation

Layer With PVD				*Layer Without PVD*			
U_1%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)	U_2%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)
0%	0,00	0,0000	0,5636	0%	0,0000	0,0000	0,2934
5%	1,87	0,0282	0,5354	5%	4,6183	0,0147	0,2787
10%	3,74	0,0564	0,5072	10%	18,4731	0,0293	0,2640
15%	5,77	0,0845	0,4791	15%	41,5645	0,0440	0,2494
20%	8,14	0,1127	0,4509	20%	73,8925	0,0587	0,2347
25%	10,57	0,1409	0,4227	25%	115,4571	0,0733	0,2200
30%	13,31	0,1691	0,3945	**30%**	**166,2582**	**0,0880**	**0,2054**
35%	16,19	0,1973	0,3663	**35%**	**226,2959**	**0,1027**	**0,1907**

Layer With PVD				*Layer Without PVD*			
U_1%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)	U_2%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)
40%	19,32	0,2254	0,3382	40%	295,5701	0,1173	0,1760
45%	22,80	0,2536	0,3100	45%	374,0809	0,1320	0,1613
50%	26,57	0,2818	0,2818	50%	461,8283	0,1467	0,1467
55%	30,64	0,3100	0,2536	55%	558,8123	0,1613	0,1320
60%	35,35	0,3382	0,2254	60%	665,0328	0,1760	0,1173
65%	40,66	0,3663	0,1973	65%	800,6090	0,1907	0,1027
70%	46,96	0,3945	0,1691	70%	947,5226	0,2054	0,0880
75%	54,24	0,4227	0,1409	75%	1121,2846	0,2200	0,0733
80%	63,24	0,4509	0,1127	80%	1333,9520	0,2347	0,0587
85%	74,77	0,4791	0,0845	85%	1608,1280	0,2494	0,0440
90%	91,18	0,5072	0,0564	90%	1994,5574	0,2640	0,0293
95%	**119,21**	**0,5354**	**0,0282**	95%	2655,1627	0,2787	0,0147
99%	**184,53**	**0,5580**	**0,0056**	99%	4189,0409	0,2904	0,0029

Depth Variation: 60%

The results of the analysis at 60% depth variation can be seen in Table 8 as follows

Table 8. Empirical analysis result for 60% depth variation

Layer With PVD				*Layer Without PVD*			
U_1%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)	U_2%	t (hari)	S_c (m)	$S_{c\ residu}$ (m)
0%	0,00	0,0000	0,4658	0%	0,0000	0,0000	0,3911
5%	1,81	0,0233	0,4425	5%	8,2103	0,0196	0,3716
10%	3,61	0,0466	0,4192	10%	32,8411	0,0391	0,3520
15%	5,42	0,0699	0,3959	15%	73,8925	0,0587	0,3325
20%	7,85	0,0932	0,3727	**20%**	**131,3645**	**0,0782**	**0,3129**
25%	10,17	0,1165	0,3494	**25%**	**205,2570**	**0,0978**	**0,2934**
30%	12,89	0,1397	0,3261	30%	295,5701	0,1173	0,2738
35%	15,58	0,1630	0,3028	35%	402,3038	0,1369	0,2542
40%	18,77	0,1863	0,2795	40%	525,4580	0,1565	0,2347
45%	21,88	0,2096	0,2562	45%	665,0328	0,1760	0,2151
50%	25,71	0,2329	0,2329	50%	821,0281	0,1956	0,1956
55%	29,26	0,2562	0,2096	55%	993,4440	0,2151	0,1760
60%	33,93	0,2795	0,1863	60%	1182,2805	0,2347	0,1565
65%	39,12	0,3028	0,1630	65%	1423,3049	0,2542	0,1369
70%	44,98	0,3261	0,1397	70%	1684,4847	0,2738	0,1173
75%	51,68	0,3494	0,1165	75%	1993,3948	0,2934	0,0978
80%	60,75	0,3727	0,0932	80%	2371,4702	0,3129	0,0782
85%	71,81	0,3959	0,0699	85%	2858,8942	0,3325	0,0587
90%	87,60	0,4192	0,0466	90%	3545,8797	0,3520	0,0391
95%	**114,43**	**0,4425**	**0,0233**	95%	4720,2893	0,3716	0,0196
99%	**175,15**	**0,4612**	**0,0047**	99%	7447,1838	0,3872	0,0039

Depth Variation: 50%

The results of the analysis at 50% depth variation can be seen in Table 9 as follows

Table 9. Empirical analysis result for 50% depth variation

Layer With PVD				*Layer Without PVD*			
U_1%	**t (hari)**	**S_c (m)**	**$S_{c\ residu}$ (m)**	**U_2%**	**t (hari)**	**S_c (m)**	**$S_{c\ residu}$ (m)**
0%	0,00	0,0000	0,3680	0%	0,0000	0,0000	0,4889
5%	1,73	0,0184	0,3496	5%	12,8286	0,0244	0,4645
10%	3,46	0,0368	0,3312	10%	51,3143	0,0489	0,4400
15%	5,19	0,0552	0,3128	**15%**	**115,4571**	**0,0733**	**0,4156**
20%	7,52	0,0736	0,2944	**20%**	**205,2570**	**0,0978**	**0,3911**
25%	9,79	0,0920	0,2760	25%	320,7141	0,1222	0,3667
30%	12,42	0,1104	0,2576	30%	461,8283	0,1467	0,3423
35%	15,08	0,1288	0,2392	35%	628,5997	0,1711	0,3178
40%	18,17	0,1472	0,2208	40%	821,0281	0,1956	0,2934
45%	21,25	0,1656	0,2024	45%	1039,1137	0,2200	0,2689
50%	24,98	0,1840	0,1840	50%	1282,8565	0,2445	0,2445
55%	28,52	0,2024	0,1656	55%	1552,2563	0,2689	0,2200
60%	33,10	0,2208	0,1472	60%	1847,3133	0,2934	0,1956
65%	38,19	0,2392	0,1288	65%	2223,9139	0,3178	0,1711
70%	43,97	0,2576	0,1104	70%	2632,0073	0,3423	0,1467
75%	50,60	0,2760	0,0920	75%	3114,6794	0,3667	0,1222
80%	59,50	0,2944	0,0736	80%	3705,4222	0,3911	0,0978
85%	70,42	0,3128	0,0552	85%	4467,0222	0,4156	0,0733
90%	86,01	0,3312	0,0368	90%	5540,4371	0,4400	0,0489
95%	**112,54**	**0,3496**	0,0184	95%	7375,4520	0,4645	0,0244
99%	**174,68**	**0,3644**	0,0037	99%	11636,2246	0,4840	0,0049

Summary

Summary of the empirical analysis results can be seen in Table 10 and Figure 1 as follows.

Table 10. Empirical analysis summary

Depth variation	**Uav day 180**	**Sc residu day 180 (m)**
100%	0,98	0,0129
90%	0,97	0,0248
80%	0,88	0,1123
70%	0,78	0,2083
60%	0,69	0,3048
50%	0,59	0,4014

Table 10 above is a recapitulation of the results of the empirical analysis. If we look at the consolidation degree criteria, it is found that on the 180th day the variations that have reached a consolidation degree of 90% are the 90% and 100% depth variations. Meanwhile, if we look at the primary consolidation residue criteria, it is found that variations with values below 0.3 m are variations of 70%, 80%, 90% and 100%.

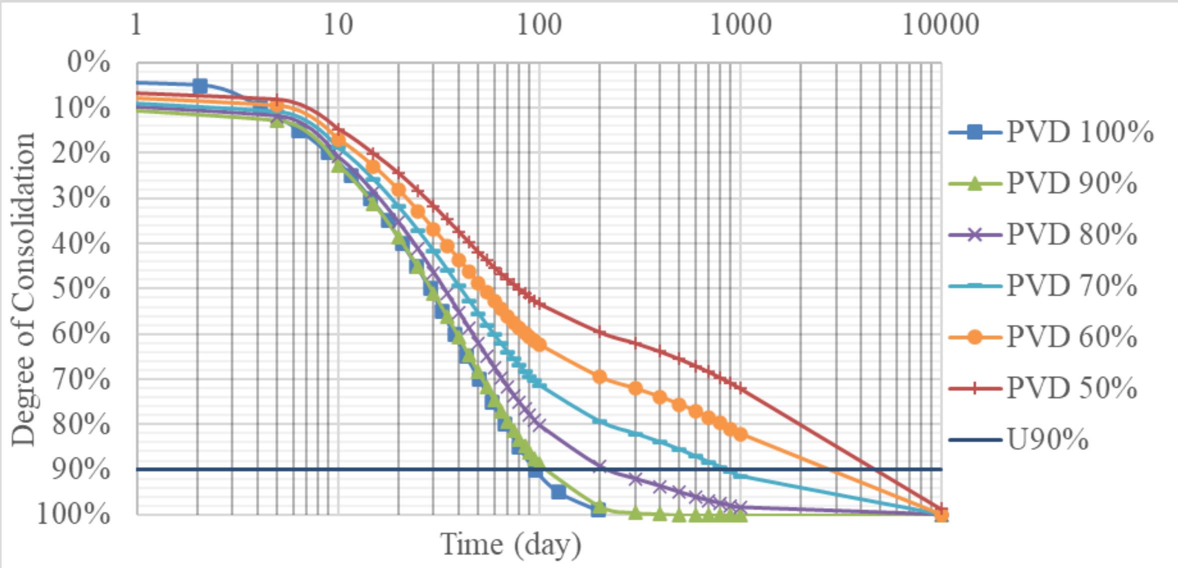

Figure 1. Summary time vs degree of consolidation

Figure 1 above shows that significant differences begin to appear from depth variations of 80%, 70%, 60%, and 50%.

Conclusion

The results of the analysis of conventional calculations using the Hansbo method showed that the effective depth when viewed in terms of the degree of consolidation was 90% on the 180th day and was within a 90% variation. Meanwhile, if viewed from the perspective of the consolidation residue that occurred on day 180, it was at a variation of 70%. Based on the results of the empirical analysis, it can be concluded that the effective depth of PVD installation varies between 70% -90%.

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