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The application of PVDs to hydraulic engineering

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ABSTRACT: PVDs (Prefabricated vertical drains) are the most extensive way to speed up the consolidation of the soft soil foundation. At present, for some reason, study of PVDs mostly is before construction. When PVDs have been constructed, the research was almost vacancy. So, the study about PVDs after constructed is very necessary. After application of PVDs to hydraulic engineering and field observation, aspects are analyzed in this paper as follows: (1) Engineering tests on the variation of discharge capacity, tensile strength and permeability coefficient, which have been done after large soft soil deformation taking place and PVDs installed into the earth for two years; (2) Analyses on the variation of the soft soil performance after application of PVDs for two years; (3) Assessment and analyses on the results of the foundation treatment by PVDs, and validation of the criterion controlling the soil stability in-situ using observation data under construction.

1 INTRODUCTION

With the rapid development of economy, Zhejiang Province is rich in the resource of tidal flats that is developed and used for making polders, aquaculture and salt industries in recent years. The sea dikes for the polders are normally made of earth and stone and the foundation of deep weak soils that require to be reinforced. To use PVDs during dike filling is the commonly effective way to speed up the consolidation of the foundation (e.g., Weibing Zhao et al. 2002). At present, for some reason, study of PVDs mostly is before construction (e.g., Yan Lou, 1999). When PVDs have been constructed, the research was almost vacancy. So, the study about PVDs after constructed is very necessary.

The southern Donghaitang reclamation project in Wen Ling County in China Zhejiang Province is composed of lots hydraulic buildings, such as closure dams, sea dikes and sluices. The reclamation area is about 33.68 km^2. The site condition is worse for the bearing strata consisted of deep and thick mucky cohesive soil and muck. Hence, by installing PVDs with an interval of 1.4 m and depth of 16 m, the soft soil foundation can be improved

In the representative location along the dike, a double-beat sluice will be established. Firstly, PVDs should be installed. After the ground was consolidated for a certain time, the foundation was excavated. And the sluice was built on after R.C. prefabricated piles were placed.

Despite there are many studies related to performance of PVDs, there still lack investigations on the observations of PVDs after placed into the earth for a certain time. Hence, to carry out the study of the performance of PVDs placed in the soft soil for two years is of actual importance for other engineering projects.

Several typical PVDs installed in the soft soil for two years has been chosen to examine their properties and to study the variation of tensile strength, discharge capacity of the cores, tensile strength and coefficient of permeability of the filters; study on the variation of the performance indexes of soft soils has been carried out; the results of the ground treatment have been analyzed. Meanwhile, the stability indexes during the construction of sea dike have been validated.

2 PROPERTIES OF PVDS

One piece of PVDs vertically and continuously takes three specimens with a length of 50 cm respectively. Dates of June 25, 2001 and May 22, 2003 are the time when PVDs installed into the ground and excavated to take the specimens respectively. Therefore, PVDs have been applied in the soils for two years or so.

PVDs are manufactured as a core with geotextile filter wrapped around it. The major mechanical properties of PVDs are summarised in Table 1.

Table 1.1 Properties of cores.

Elevation (m)	Tensile strength (kN/10 cm)	Discharge capacity	
		Bended (cm^3/s)	Straight (cm^3/s)
–1.0~–1.5	2.6	47	53
–1.5~–2.0	2.7	19	38
–2.0~–2.5	2.6	34	68
Before construction	3.1	50	50
Material requirements	1.3	25	25

Table 1.2 Properties of filters.

Elevation (m)	Tensile strength (N/cm)	Permeability (cm/s)
–1.0~–1.5	41	6.28×10^{-2}
–1.5~–2.0	36	1.49×10^{-2}
–2.0~–2.5	39	5.83×10^{-2}
Before construction	47	3.87×10^{-2}
Material requirements	18	5.00×10^{-4}

2.1 *Properties of the cores*

The major mechanical properties of the cores are tensile strength and discharge capacity.

2.1.1 *Tensile strength*

Before construction, the mean tensile strength was 3.1 kN/10 cm. After application for two years, the mean tensile strengths of the core specimens at the three different depths are 2.6 kN/10 cm, 2.7 kN/10 cm and 2.6 kN/10 cm respectively. The mean tensile strength of the core decreases obviously, and discounting coefficient is about 81%~88%. However, the demand of the construction can be met, and that is, the mean tensile strengths of the cores were equal and more than 1.3 kN/10 cm.

2.1.2 *Discharge capacity*

Before construction, the mean discharge capacity of the cores was 50 cm^3/s. When being loaded, PVDs were partly bended, and partly still straight. The examination of the discharge capacity under two conditions is as follows:

One is straight condition. After application for two years, the mean discharge capacities of the core specimens in three depths is respectively 53 cm^3/s, 38 cm^3/s and 68 cm^3/s. The other is bended condition. After application for two years, the mean discharge capacity of the core specimens in three depths is 47 cm^3/s, 19 cm^3/s and 34 cm^3/s respectively.

It shows that after two years, the mean discharge capacity of the cores in straight condition is required more than 25 cm^3/s, while that of the cease falls a lot. After PVDs were bended, discharge capacity of the cores fell to some extent which was larger than that under the straigt condition. And requirements of the only one piece failed to be met. It is 19 cm^3/s, less than 25 cm^3/s.

2.2 *Properties of geotextile filters*

The major mechanical performance indexes of the filters are tensile strength and coefficient of permeability.

2.2.1 *Tensile strength*

Before construction, the mean tensile strength of the filters is 47 N/cm. After application for two years, the mean tensile strength of the filter specimens in three depths is respectively 41 N/cm, 36 N/cm and 39 N/cm. It shows that after two years, the mean tensile strength of the filters has fallen obviously. And discount coefficient is about 59%~90%. However, it meets demands under construction, and that is, the mean tensile strengths of the filters are equal or more than 18 N/cm.

2.2.2 *Coefficient of permeability*

Before construction, the mean coefficient of permeability of the filters is 3.87×10^{-2} cm/s. After two years, the mean coefficient of permeability of the filter specimens in three depths is respectively 6.28×10^{-2} cm/s, 1.49×10^{-2} cm/s, and 5.83×10^{-2} cm/s.

Comparing with the two periods, coefficient of permeability of the filters is in the same order, which is 10^{-2} cm/s. It's clear that loading has fewer effects on the coefficient of permeability of the filters.

3 PERFORMANCE INDEXES OF SOILS

3.1 *Site conditions*

Engineering geologic exploration shows that there are two soft soil strata (Table 2.1):

Hence, both C1 and B1 are high water content and high compressibility soft soils. The strata are thick with low strength and it has worse geologic conditions.

3.2 *Test results of soft soil after loaded and consolidated*

After soft soil is loaded and consolidated, the shear strength of which raises. Two bore-holes made by manual-pushing boring and five specimens are obtained at each hole. The upper elevations of two bore-holes are –1.0 m. Test results are listed in Table 2.2. By comparing Table 2.1 with Table 2.2, it shows that the foundation of the sluice is mainly the muck stratum, which is illustrated as soil stratum B1.

Table 2.1 Soil characteristics of natural foundation.

Soil stratum	Water content (%)	Density (g/cm^3)	Void ratio	Undrained shear C (kPa)	Undrained shear (°)
C1	43.9~48.9	1.74~1.78	1.25~1.35	5.9~6.6	1.5~1.9
B1	50.3~66.0	1.63~1.74	1.37~1.78	5.2~15.2	1.0~3.8

Soil stratum	Consolidated undrained shear C (kPa)	Consolidated undrained shear ϕ (°)	Modulus of compressibility (MPa)	Static cone penetration (MPa)
C1	13.0~18.2	14.6~16.0	2.0~2.4	0.1~0.2
B1	7.2~15.7	11.3~14.9	1.2~2.2	0.2~0.4

C1–Mucky cohesive soil, grey, saturated, flow plasticity, high compressibility. Besides, it takes on distribution of lens; the upper slab level is from –0.58 m to –1.90 m; static cone penetration is qc = 0.1~0.2 MPa, fs = 6~8 kPa.

B1—Muck, grey to light blue, saturated, flow plasticity, high compressibility. It partly has a few white crushed shells. Upper slab level is from –0.44 m to –19.70 m. Static cone penetration is qc = 0.2~0.4 MPa, fs = 6~10 kPa. Vane strength is Cu = 6~24 kPa, which can be taken as the tread line i.e. Cu = 5.780 + 0.919Z (Z is the hole depth, m).

Table 2.2 Soil characteristics after consolidation.

Item	Elevation (m)	Water content (%)	Density (g/cm^3)	Void ratio	Undrained shear C (kPa)	Undrained shear ϕ (°)
1–1	–1.5	43.8	1.77	1.226	5.0	7.0
1–2	–2.5	42.0	1.80	1.154	5.0	9.7
1–3	–3.5	44.0	1.78	1.209	8.0	7.8
1–4	–4.5	45.7	1.75	1.383	8.0	7.0
1–5	–5.5	52.2	1.75	1.311	8.0	8.0
2–1	–1.5	47.6	1.75	1.131	6.0	7.5
2–2	–2.5	40.8	1.81	1.131	5.0	10.0
2–3	–3.5	44.5	1.78	1.232	9.0	9.1
2–4	–4.5	45.4	1.77	1.259	8.0	9.5
2–5	–5.5	47.6	1.75	1.319	7.0	8.5

Continued (Table 2.2)

Item	Elevation (m)	Consolidated undrained shear C(kPa)	Consolidated undrained shear ϕ(°)	Modulus of compressibility (MPa)
1–1	–1.5	8.0	20.2	2.2
1–2	–2.5	8.0	20.8	2.3
1–3	–3.5	8.0	21.0	2.4
1–4	–4.5	8.0	20.5	2.1
1–5	–5.5	8.0	18.6	1.7
2–1	–1.5	7.0	18.3	2.1
2–2	–2.5	10.0	21.3	2.7
2–3	–3.5	9.0	21.0	2.3
2–4	–4.5	8.0	18.2	1.9
2–5	–5.5	7.0	18.5	1.8

3.3 *Contrasting of performance indexes before and after soil improvement*

After comparison the test results of soft soil under construction with that after loaded and consolidated, several useful proposals are recommended as follows:

3.3.1 *Water content*

Before construction, water content of soft soil is 50.3~66.0%, while in the improved soft soil, water content of the bore-hole 1 is 42~52.2% and that of the bore-hole 2 is 40.8~47.6%. After improvement, water content in soft soil decreased obviously. Therefore, it's effective on the consolidation. In addition, the effect of improvement decreased in the deeper locations.

3.3.2 *Density*

Before construction, density of soft soil was 1.63~1.74 g/cm^3. By improving soft soil, destiny of which is 1.75~1.80 g/cm^3 at bore-hole 1 and 1.75~1.81 g/cm^3 at bore-hole 2. It's clear that the density of soft soil has increased after improved.

3.3.3 *Void ratio*

Before construction, void ratio of soft soil was 1.37~1.78. After improving soft soil, void ratio is 1.154~1.383 at bore-hole 1 and is 1.131~1.319 at bore-hole 2. Henceforth, it's obvious that void ratio of soft soil decreased.

3.3.4 *Strength indexes*

Before construction, cohesion of undrained shear test of soft soil was 5.2~15.2 kPa, and the angle of internal friction was 1.0~3.8°. By improving soft soil, cohesion of undrained shear test for bore-hole 1 is 5~8 kPa, and the angle of internal friction is 7.0~9.7°. Cohesion of undrained shear test for bore-hole 2 is 5~9 kPa , and the angle of internal friction is 7.5~10.0°.

Before construction, cohesion of consolidated undrained shear test of soft soil was 7.2~15.7 kPa, and the angle of internal friction was 11.3~14.9°. By improving soft soil, cohesion of consolidated undrained shear test for bore-hole 1 is 8 kPa, and the angle of internal friction is 18.6~21.0°. Cohesion of consolidated undrained shear test for bore-hole 2 is 7~10 kPa, and the angle of internal friction is 18.2~21.3°.

After improved, cohesion of undrained shear test and consolidated undrained shear test of soft soil vary unremarkably. But the angle of internal friction increases obviously.

3.3.5 *Modulus of compressibility*

Before construction, modulus of compressibility of soft soil is 1.2~2.2 MPa. As to the improved soft soil, modulus of compressibility for bore-hole 1 is 1.7~2.4 MPa, and is 1.8~2.7 MPa for bore-hole 2. Modulus of compressibility of soft soil increased obviously by improvement. The effect of improvement decreases with the depth.

To sum up, after soft soil is loaded and consolidated, performance indexes of it have improved to a certain degree. The stability of the sea dike has increased accordingly to some extent.

4 THE EFFECT OF SOIL IMPROVEMENT AND THE STABILITY INDEXES CONTROLLING CONSTRUCTION

4.1 *The effect of soil improvement*

Before and after consolidation in the project, the shear strength of the soft soil has been measured by in-situ vane shear test. The results are summarised in Figure 1. It shows that comparing with the vane strength of the natural foundation, soft soil of which after loading and consolidation has obviously on the rise. Besides, the increment decreased with depth. C_{u1} and C_{u2} as follows are respectively on behalf of circumstances of natural foundation and after consolidation.

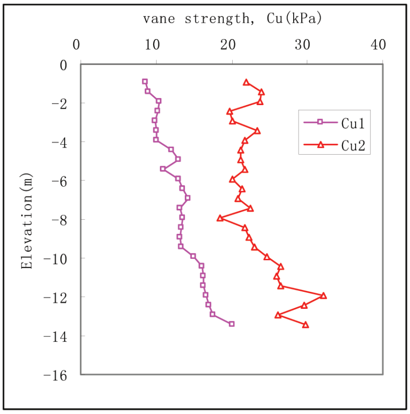

Figure 1. Test results of vane strength.

4.2 *The stability indexes controlling construction*

According to relevant regulations, standards, related engineering experience and the loading plan of geology and schedule of this project, the control indexes of stability in construction period is put forward as follows:

(1) Vertical deformation, the rate of settlement is equal and less than 2.0 cm/d.
(2) Lateral deformation, the daily lateral movement is less than 4 mm.
(3) Pore water pressure ratio, B is less than 0.6.

In the process of construction, the rate of settlement was greater than 2.0 cm/d at the beginning of loading because of silt displacement. After about two days, the rate of settlement fell to less than 2.0 cm/d. Besides, both the daily lateral movement and pore water pressure ratio didn't exceed above control value. During the loading process, sea dike was stable. On the basis, it indicated clearly that it was suitable for the stability indexes presented in construction period for this project.

5 CONCLUSIONS

According to analyses above, several interesting conclusions are drawn on as follows:

(1) After application for two years, the mean tensile strength of the cores has obviously fallen. Discount coefficient is within 81%~88%, which proved that the mean tensile strength of the cores is affected essentially after application in the soft soil foundation for two years. Therefore, designers should take this factor into account.
(2) After two years, the mean discharge capacity of the cores varies a little in straight condition and it obviously decreases in the bended one, e.g., one piece cannot meet the material requirements, which is 19 cm^3/s, less than 25 cm^3/s. So this factor should be considered in design.
(3) After two years, the mean tensile strengths of the filters has fallen obviously, and discount coefficient is about 59%~90%, which should be taken into account in design.
(4) As it is stable for coefficient of permeability. Coefficient of permeability is at the same order of 10^{-2} cm/s before constructed and after loaded for two years.
(5) By means of loading and pore pressure dissipating, performance indexes of soils, to a certain degree, have been improved. The stability of the sea dike has been raised accordingly.
(6) Vane strength of the foundation goes up remarkably after improved. Likewise, it's evident for the function of PVDs.
(7) The rate of settlement is equal and less than 2.0 cm/d; the daily lateral movement is less than 4 mm; the pore water pressure ratio B is less than 0.6. These comprehensive and stable controlling standards above play a better role in this project under construction.

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