Chapter 7
Application of Prefabricated Vertical Drains (PVDs) for Improvement of Soft Clays—A Case Study

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Introduction

Project Details

The current case study is concerning a facility located at Navi Mumbai. The project consists of warehouses, office buildings, container yard, internal roads, apron, pavers, and other ancillary buildings. The total site area of the following case study was around 1,79,000 m^2 (Approx. = 44 Acres). The site of the concerned case study is nearby sea and the approximate distance from the sea was 6.0–7.0 km. The soil profile of the site was the real challenge in the project, and this case study is about how the design team overcomes this problem related to geotechnical engineering. The soil strata of the following case study consist of filled up soil with boulders varying from a depth of 3.0–4.0 m followed by very soft marine clay up to a depth of 12.0–13.0 m from Existing Ground Level (EGL), i.e., the soft clay layer thickness was around 9.5 m. Soft clay was followed by hard/stiff clay up to the weathered/hard rock top. The rock top was varying from a depth of 14.0–26.0 m throughout the site. The soil was subjected to various loads consisting of structural loads (dead load, live load, wind, and earthquake loads), racking loads from grade slab in warehouses, vehicular loads on external sections, and container stacking load in container yards. Detailed study of strata was done through the soil investigation, preliminary surveys, and site visits. Based on the study, it was found that the soft clay layer was highly compressible in nature and highly susceptible to settlements on loading. If the construction takes place without ground improvement on such kinds of soils, it can cause excessive

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settlements which may lead to damage to the structure and affect the serviceability of the project and the structures.

Hence, to deal with the problem mentioned in the above paragraph, ground improvement was proposed. Based on the detailed study and analysis, Prefabricated Vertical Drains (PVDs) with surcharge were adopted as the most suitable option for improving the ground in this project and after the successful completion of the ground improvement process, and PVD with surcharge proved to be a most suitable and feasible solution. This case study will depict the application of PVD with surcharge technique of ground improvement at the concerned site.

Soil Investigation

Before design and execution of any ground improvement activity, we need to have detailed soil investigation parameters and comprehensive knowledge of soil profile of the site. Also, before adopting any ground improvement, we investigate the feasibility of the technique and other practical and economical aspects of the ground improvement technique. Apart from 10 boreholes in the tender stage, to acquire detailed parameters of soil, 27 boreholes and 15 trial pits were proposed in the concerned project. The depth of boreholes was up to the rock layer and the depth of trial pits was up to the top of the soft clay layer. The depth of boreholes and trial pit was decided such that we can estimate the approximate depth of rock top throughout the site. Field tests such as standard penetration test and vane shear test were conducted at the site, and samples were collected for laboratory tests. Oedometer test for consolidation parameters of soil was conducted in the laboratory. The groundwater table at the site was around a depth of 1.0–2.0 m from the Existing Ground Level (EGL). Design parameters adopted are given in Table 7.1. Also, the proposed boreholes and trial pits are shown in Fig. 7.1.

Table 7.1 Design parameters derived from soil testing

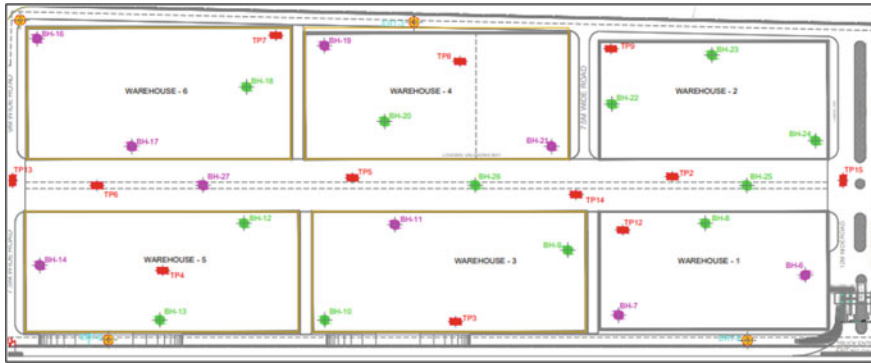| Layer	Description	Depth of layer from EGL	Layer thickness	Cohesion (KN/m^2)	Angle of friction (Degree)	Bulk unit weight (KN/m^3)	Average field SPT N values
Layer 1	Filled up soil with boulders	0–3.5 m	3.5 m	–	28	19	15–20
Layer 2	Very soft to soft clay	3.5–12.5 m	9.0 m	10	–	15.5	0–3
Layer 3	Hard stiff clay	12.5–18 m	5.0 m	100	–	18	30–40
Layer 4	Weather/hard rock	>18.0 m	–	–	40	20	Refusal

Fig. 7.1 Borehole and trial pit layout for warehouse area of the site

Ground Improvement Features

Selection of Technique

Based on the preliminary study of the project and soil investigation, it was observed that the consolidation of the soft clay layer was required to arrest the excessive settlement of structures in the future after construction. Another option was to transfer the load directly to hard strata, and the second option may be suitable for structural loads through pile foundation, but grade slab and pavement loads are not feasible practically to transfer to hard stratum. Hence, the first option was considered, i.e., consolidation of soft clay.

Consolidation: When cohesive soils which are saturated in nature, either fully saturated or partially saturated, are subjected to applied stress, the volume of saturated soils decreases and results in the reduction of compressibility of soil. In this process, removal of water takes place from the voids of soil and generally, and it is observed in clayey soils only.

There are various methods for consolidation of clayey soil. In this project, number of methods were analyzed such as stone columns, rigid inclusions, preloading, PVDs with vacuum consolidation, and drains/PVD with surcharge. Based on several factors such as availability of literature, requirement of skilled labor, feasibility at the site, equipment and vendor availability, time consumption, and cost, Prefabricated Vertical Drains (PVDs) with surcharge were adopted as ground improvement method for the project.

PVD will provide a shorter drainage path to water, to come out from the impervious strata, i.e., clay and surcharge will be generating the stress in the clayey soil which will ultimately force the water to come out of the soft clay.

Component of Ground Improvement

The ground improvement technique of PVD with surcharge consists of number of components which are described in this section.

Prefabricated Vertical Drains (PVDs): PVDs consist of a central core, which will act as a free drainage channel, and a non-woven filter jacket, which prevents the soil surrounding the drain from entering the central core but allows water to flow in. Vertical drains are installed under a surcharge load to accelerate the drainage of impervious soils and thus speed up consolidation. These drains provide a shorter path for the water to flow through to get away from the soil.

The use of PVDs is applicable for soils which are moderate to highly compressible under static loading and compress very slowly under natural drainage conditions due to low soil permeability and relatively great distance between natural drainage boundaries. Soils with these characteristics are almost exclusively cohesive, fine grained soils, either organic or inorganic. In this project, PVD of 12 m depth was installed in triangular pattern, from the existing ground and terminated in stiff clay layer. For faster execution of project, total site was divided in two phases based on spacing of PVDs. In phase 1 of the project, 0.8 m spacing of PVD was adopted, and in Phase 2 of the project, 1.0 m of PVD spacing was adopted.

Surcharge: Soil was used to apply pressure to the soft clay layer which results in generation of pore water pressure in the clayey soils. A surcharge of height varying from 2.5 m to 5.5 m was adopted in the project. The surcharge height was depending upon the load requirements of various structures. The surcharge was divided into two layers, namely, permanent surcharge and temporary surcharge to fasten the execution process.

Drainage Layer: It consists of drainage material that allow dissipation of pore water pressure generated due to surcharge. A drainage layer of 0.5 m thickness was provided in the present case study.

Geotextile: A layer of geotextile was used to prevent the blockage of drainage layer during the process of consolidation.

Monitoring Instruments: Monitoring instruments such as settlement gauges, vibrating wire piezometers, and post vane shear test were used to monitor the ground improvement process and results.

Details related to the ground improvement scheme are provided in Table 7.2 and components of ground improvement are shown in Fig. 7.2.

Design Parameters

PVD + Surcharge method of consolidation is designed to get an optimized PVD spacing, PVD depth, and waiting period of the total system. For design of ground

Table 7.2 Ground improvement scheme

| Parameters	Value
Soft clay layer thickness, H	9.5 m
Time for consolidation without ground improvement	95 years (considering single drainage)
Ground improvement method recommended	PVD + Surcharge
Pattern of PVD	Triangular
Spacing of PVD	0.8 m (Phase 1) and 1.0 m (Phase 2)
Length of PVD (excluding projections)	12.00 m
Total surcharge height (depending on load requirement)	5.50 m, 5.00 m, and 2.50 m
Drainage layer thickness	0.50 m
Time for 90% consolidation	90 days (Phase 1) and 150 days (Phase 2)
Number of stages for surcharge application	ONE
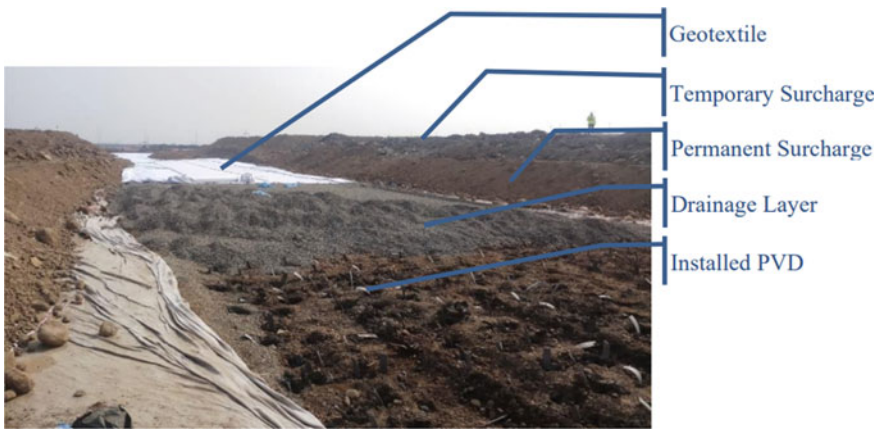
Fig. 7.2 Components of ground improvement

improvement system, various parameters were considered based on the soil investigation, codal provisions, and design engineer experience. Table 7.3 provides the detail of design parameters considered for design of the ground improvement system of the project. Ratio $Cc/(1 + e_0)$ is around 0.180 result in higher consolidation settlements and shows that soil is highly compressible in nature. Single drainage was considered for design as the soft clay layer was followed by an impervious layer of stiff to hard clay layer. Area treated by single PVD, A, and equivalent diameter of band drain, d,

Table 7.3 Design parameters for design of ground improvement system

Design parameters	Value
Soil property	
Liquid limit of soft clay	75%
Plastic limit of soft clay	40%
Plasticity index	35%
Specific gravity	2.65
Void ratio	2.25
Compression index (Cc)	0.585
Coefficient of vertical consolidation, Cv	0.8 m^2/Year
Coefficient of horizontal consolidation, Ch	1.6 m^2/Year
Drainage	Single
Drainage path (equal to thickness of soft clay layer)	9.5 m
PVD properties	
Width of band drain b	100 mm
Thickness of band drain t	4 mm
Area treated by single band drain, A	0.555 m^2
Equivalent diameter of cylindrical column, D	0.840 m
Equivalent diameter of band drain, d	0.067 m
Degree of radial consolidation, Ur	90%

depends on the pattern of the PVD, in which it is installed and the dimensions of the PVD. Degree of consolidation means the amount of consolidation designer wants to achieve through this system and by achieving the desired degree of settlement future settlements can be maintained within permissible limits. In this case, study degree of consolidation for which design has been done is 90%.

Analysis Steps

Consolidation Time Calculation

Consolidation of soft clay layer would have taken place without PVDs and surcharge as well, but it would have taken a lot more time as compared to that of present condition. Hence, during analysis, time for 90% consolidations was calculated, for the condition without PVD as well as, with PVD and surcharge. The time for without PVD condition was calculated using Eq. 7.1.

$$t = \frac{T_v * d2}{C_v} \tag{7.1}$$

where T_v is the time factor depending on the degree of consolidation, d is the drainage path, in the following case study it is taken as 9.5 m, which is equal to the clay layer thickness, and C_v is the coefficient of vertical consolidation C_v. The time without ground improvement was 95 years.

Now, to reduce the time of the consolidation, we have introduced the PVD into the clayey layer. Hence, to calculate the time for 90% of consolidation, Hansbo's Equation [2] was used. Equation 7.2 shows Hansbo's Equation

$$t = \frac{D^2}{8.Ch} \cdot \left[\frac{1}{1-(d/D)^2} \cdot \ln(d/D) - \frac{3}{4} + \frac{1}{4}\left(\frac{d}{D}\right)^2 \right] \cdot \ln\left(\frac{1}{1-U}\right) \qquad (7.2)$$

Using above equation time for consolidation came out to be 84 days, hence 90 days were kept as a waiting period for PVD spacing of 0.8 m. Similarly, for phase 2, 150 days were kept as the waiting period with PVD spacing of 1.0 m.

Surcharge Height Calculation

As shown earlier in the article that the surcharge height was kept different for different loads and structures. The surcharge height depends on the estimated future load going to be exerted on soil after construction of structure. The same load will be applied to soil during the waiting period. Hence, the surcharge is also known as preloading. The load on the soil shall be the combination of dead load of section and live load of structure. For example, in the present case study, in warehouse area, total load was around 100 KN/m^2 and the density of surcharge was considered 18 KN/m^3, hence, the total surcharge height in the grade slab area was 5.50 m. Similarly, for yard area surcharge, height was 5.0 m, and for pavement area, it was around 2.50 m.

Increase in Cohesion Value

With removal of water, soil will be compressed and result in stiff and hard clay. Indirectly, this will result in an increase in the cohesion value of the soil. During the initial soil investigation, the cohesion value of the soft clay layer was around 15 KN/m^2, and after ground improvement, the cohesion value increased and the same was estimated using the equation from the IRC75-2015: GUIDELINES FOR THE DESIGN OF HIGH EMBANKMENTS. The equation used for computation of final cohesive value is shown in Eq. 7.3.

$$\Delta c = k \times U \times \Delta\sigma \qquad (7.3)$$

where Δc is gain in cohesion after ground improvement, U is the degree of consolidation achieved after ground improvement, and $\Delta\sigma$ is the increase in the effective pressure at the center of the soft clay layer due to the surcharge loading.

Degree of consolidation can be calculated using the equation provided in clause 6.5.2 of IS15284-Part II: Design and Construction for Ground Improvement—Guidelines (preconsolidation using vertical drains).

The increased cohesion value for warehouses area was 37 KN/m^2. The design value calculated was validated using the field vane shear test.

Combined Degree of Consolidation

Generally, the consolidation will be taking will be radial, but the vertical consolidation will also take place. The vertical degree of consolidation can be calculated from Table 7.2 of IS15284-Part II: Design and Construction for Ground Improvement—Guidelines (preconsolidation using vertical drains). The combined degree of consolidation can be given by Eq. 7.4.

$$U = 1-(1 - U_z) * (1 - U_r) \tag{7.4}$$

The combined degree of consolidation for the concerned project was estimated as 91.57%.

Settlement Computations

Consolidation settlement was computed at the center of the soft clay layer using the dispersion of load from top to center as $1H$: $2V$. Equation used for computation of settlement is shown below in Eq. 7.5.

$$\Delta H = \frac{c_c.H}{1 + e_0} \times \log\left(\frac{\sigma_0 + \Delta\sigma}{\sigma_0}\right) \tag{7.5}$$

The total settlement of clayey layer was 641 mm. As per Section "Combined Degree of Consolidation" of the present article, degree of consolidation achieved during the ground improvement is 91.57%, hence, future settlement that can take place is around 54 mm which is under the permissible limits. Hence, design is safe and showing the desired result. If the future settlement is not within the permissible limits, then we need to redesign by varying the spacing of PVD and degree of consolidations.

Execution of PVD and Surcharge

Ground improvement was done in the area of 1,76,170 m^2 (43.50 acres). Execution of PVD was done in two phases as discussed in previous sections. Based on the spacings, total site was divided into two phases. This was done to maintain a balance between cost and time.

PVD Installation: PVD was installed in a triangular pattern at designed spacing using PVD rigs. The depth of installation was fixed based on the thickness of soft clay layer and depth of stiff clay so that the anchor rod can be anchored in the hard strata. In the current case study, depth of installation was 12.0 m and a projection of approximately 150 mm on each side was left. PVD was embedded in drainage layer. PVD rig can install a PVD in 40–60 s. Around 2,50,000 PVDs were installed at the site, which means approx. 30,00,000 running meter of PVD was installed. A total of 6 PVD rigs were used for the timely completion of the project.

Surcharge: Laying of surcharge was done in two types so that the time for backfilling to reach desired levels can be saved. Surcharge in the current case study was done as the combination of permanent surcharge and temporary surcharge. Temporary surcharge was removed after waiting period, while the permanent surcharge was kept as it was required to reach desired Formed Ground Level (FGL) of the site. Total surcharge quantity of 8,00,000 Cum was used in the present ground improvement system. Surcharge was also including the drainage layer.

Above numbers are proof that the current case study is one of the biggest ground improvement case studies in India (Fig. 7.3).

Results and Observations

During and after the execution of surcharge, various monitoring instruments were installed at the project site to monitor the progress of ground improvement. The instruments used were including settlement gauges and vibrating wire piezometers. For checking the final field cohesion values, field vane shear tests were proposed and conducted after waiting period.

A total of 44 settlement gauges, 22 Piezometers were installed at site and 70 post ground improvement vane shear tests were proposed. All the monitoring instrumentations were done as per the specifications of Highway Research Board (HRB) 13 and 14 manuals. Full site was divided into segments so that the maintenance of record, execution, and removal of surcharge becomes easy and timesaving.

Settlement gauges used in the present articles were plate-type settlement gauges and these gauges were installed at the top of clay layer and readings were taken using the auto-level surveying instrument. Weighted average settlement of approx. 700 mm was observed throughout the site. A maximum settlement of 1.177 mm (1.177 m) was also observed in one of the segments.

Execution   PVD Rig

Permanent Surcharge   Piezometer

Fig. 7.3 Execution images of PVD and surcharge

There was total of 44 settlement vs time curves were studied. Figure 7.4 shows some of the results of settlement vs time for various structures.

Piezometers were installed at the site before laying of surcharge. Piezometers were installed to measure the pore water pressure generation and observe the dissipation of pore water pressure. As the surcharge laying was under process, the pore water pressure was developing, reached its peak values, and as the waiting period started, the pore pressure start decreasing. It was observed that when the waiting period was about to over full pore, pressure was dissipated as the pore water pressure attains same value as the initial value or a value near to the initial value. This confirms the end of consolidation process and also validates design. If the pore pressure graph is not showing the correct curve as mentioned in the above discussion, waiting period can be increased based on the experience (Fig. 7.5).

Vane shear tests (70 Nos) were conducted after waiting period was completed. Vane shear test was done to check the increased cohesion value. During the time of soil investigation also vane shear tests were conducted. Cohesion value of both the vane shear test and design cohesion value was compared. In all the locations, the cohesion value was more than the cohesion value computed during the design stage. This shows that the soft clay which was present at the site was now consolidated
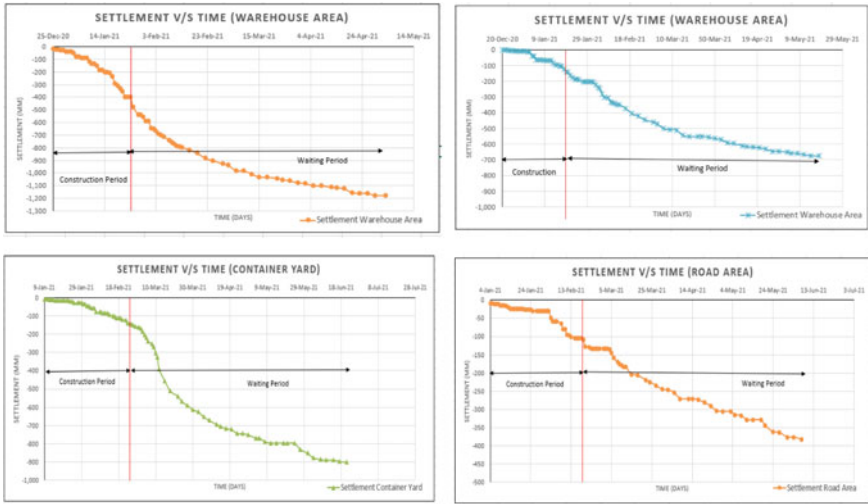
Fig. 7.4   Settlement versus time graph for various structures
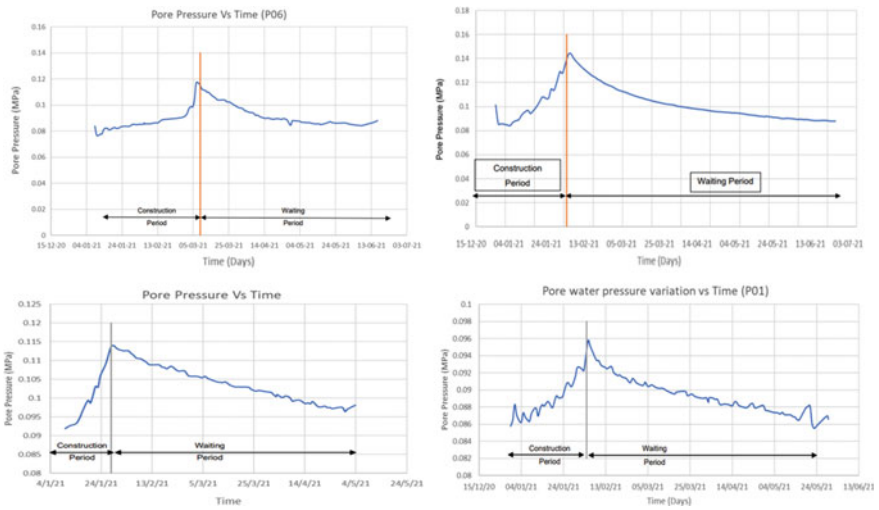

Fig. 7.5   Pore pressure versus time plots from piezometers

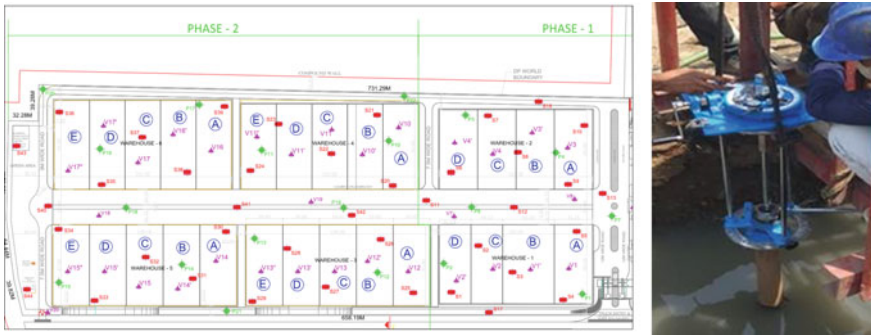and the cohesion value was increased around 5–7 times of initial cohesion value (Fig. 7.6).

Fig. 7.6 Instrumentation layout and vane shear test

Conclusions

In the following case study, we have seen problems related to soft clay, solution of the highly compressible nature of the soil. In the article, design and execution of the ground improvement technique was discussed. Application and mechanism of the PVD + Surcharge were also shown. So, after completion of the ground improvement process, following are the observations.

1. Soil strata present in any site may have uncertainties; hence, detailed soil investigation is required for correct set of inputs, and which can lead to optimization of quantities and time.
2. PVD + Surcharge method is suitable for the consolidation of soil type described in the present case study. Also, it is an effective and economical method for soft clayey soils.
3. From the piezometer results, it can be incurred that the generation of pore pressure takes place during the surcharge laying and dissipation of pore pressures takes place in the waiting period. It is observed that the pore pressure generated in was not equal to the surcharge load as the some load would have dissipated in top fill-up soil of 3.0 m height. The curve generated for pore pressure vs time from piezometers was matching the curves cited in the references.
4. Settlement observed was non-uniform. Also, settlement readings observed were 100 to 200 more than that of predicted settlement, and this may be due the fact that design was done based on laboratory parameters, and in actual, the soil parameter would have vary in field.
5. Cohesion values observed for 0.8 m spacing of PVD were more than that of 1.0 m spacing of PVD, but theoretical computation of the increased cohesion as per IRC 75–2015[2] does not take spacing of PVD into account.
6. Phased wise approach, segmental surcharge laying, and two types of surcharges can be adopted depending upon the project requirement to optimize the cost and time of execution.

As India is having around 7517 km long coastline, which is having a higher probability of having marine soft clay along the coast, hence, there is major scope of Prefabricated Vertical Drains with surcharge in India. As a future scope or research, we can study the detailed affect of spacing of PVD on increased cohesion or smear effect in PVD for various mandrel size can be studied.

References

1. IS15284-Part II: design and construction for ground improvement—guidelines (Pre-consolidation using vertical drains)
2. IRC:75–2015: guidelines for the design of high embankments (First Revision)
3. HRB 13: State of the Art: high embankments on soft ground—part a—stage construction
4. HRB 14: State of the Art: high embankments on soft ground—part b—ground improvement
5. IS 4434–1978: code of practice for in-situ vane shear test for soils
6. FHWA/RD-86/168: prefabricated vertical drains (vol 1—engineering guidelines)