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Importance of Verticality of PVD in Consolidation Settlement of Prefabricated Vertical Drain-Improved Soft Soils

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Abstract. This paper shows how vital the verticality of a PVD is. In this study, a physical model of measures 452 mm diameter and 600 mm high is used. The paste of silty-clay soil of medium plasticity is prepared at water content below its liquid limit. In the first case, a PVD is centrally placed before pouring the paste. In other words, a mandrel is not used in this study to eliminate its disturbance on soil mass. Soil bed with PVD is, after that, prepared in three stages. A sand layer is then placed on the top surface. Above the sand layer, the seating plate through which vertical pressure is applied is placed. On this plate, an incremental vertical pressure of 10 kPa is applied at an interval of 7 days up to 63 days, and accordingly, consolidation settlements are recorded. In the second case, a PVD is placed in such a way that it makes an angle (θ) of 4°45´ (tilted) at the bottom center of the bed, i.e., the PVD is dislocated at the upper portion by 5 cm. The same test procedure is followed here also. From the test results, it is observed that the latter case exhibits lesser settlement results as compared to the first case. It may be attributed to the clogging and buckling occurred at the upper portion of the PVD due to the non-uniform ordination of vertical pressure between the PVD faces. Therefore, it may be concluded that maintenance of its verticality should also be taken care of to achieve a larger settlement during PVD installation.

Keywords: Silty-clay soil, PVD, Inclination, Settlement, Time Period.

1 Introduction

Highly compressible soft soils possess high natural moisture content, even reach close to the liquid limit, low hydraulic conductivity, and low undrained shear strength. If proper measures are not taken to improve those soils, the structures constructed may face stability problems. However, expensive pile foundations are adopted in some cases. Now-a-days application of prefabricated vertical drains (PVDs) in the area of ground improvement has proven to be the fastest-growing method among all other techniques. Thus it plays a vital role in geotechnical engineering constructions. It includes large-scale infrastructures such as highways, railways, ports, and airports

(Indraratna et al. 2010; Karunaratne 2011; Watabe et al. 2014; Karim and Lo 2015). The time required for consolidation of the soil reduces to a few months with PVDs and preloading. However, the performance or efficiency of PVDs is dependent on many factors, such as type and discharge capacity of the PVDs, the permeability of the soil, preloading pressure and its period, type of the soil, buckling or deformation of the PVD, etc. Among all other factors, the PVD's verticality is also an influencing factor to which consolidation settlements mostly depend. In practice, sometimes, the verticality of PVDs may not be maintained due to defective machinery measures or improper monitoring arrangements during installation. Consequently, adequate functioning of the PVDs is hindered to some extent, and hence the construction completion period also may be delayed, followed by unwanted high maintenance costs.

In this paper, an attempt is made through experimental studies on PVD treated soft soils to determine the adverse effects of verticality of PVDs on consolidation settlements of the silty-clay soil. It is hoped that this research study will help the researchers and academicians working on PVDs to some extent.

2 Objectives of the present study

The present study's objectives are to determine the adverse effects of the verticality of PVD on consolidation settlements of silty-clay soil and to find out the impact of the time. Curves exhibiting consolidation deviation results (due to tilting of the PVD) are presented in this study. Hence knowledge about the significance of the verticality of PVDs is achieved from the curves.

3 Experimental Programs

3.1 Materials used in this study

The soil is classified as silty clay (CI) of medium plasticity and of greyey-white in color. The soil was collected from Ananda Nagar, Agartala, Tripura state, India. Geotechnical properties of the soil are given in Table 1. The prefabricated vertical drain was collected from Meccaferi Pvt. Ltd., India. Its breadth is 100 mm, and the width is 4 mm, so the equivalent diameter of the PVD is 66 mm. Its properties are shown in Table 2.

3.2 Laboratory model and preparation of soil paste

In this study, a physical model made of 6 mm thick steel of 452 mm internal diameter and 600 mm internal high is used. A sketch of the model is shown in Fig.1. Vertical pressures are applied with the help of a lever arm and its system. Soil is mixed with water, and paste is prepared at water content 47% (near the liquid limit) in a tray, and later the soil bed is prepared in stages inside the model along with a PVD.

3.3 Test procedure

In this study, PVDs are pre-inserted, i.e., no mandrel is used to install the PVD eliminating soil disturbance. Two cases had been studied: (i) Vertical PVD and (ii) Tilted PVD. In both cases, the magnitudes of vertical pressures and time are kept the same. The ray diagram of this arrangement is shown in Fig.1.

(i) Vertical PVD. In this case, a PVD is, firstly, placed centrally inside the model, making an angle of 90° (φ) with the model base. Then soil paste is poured inside it in three stages, keeping the soil's undrained shear strength as 20 kPa. A polythene paper is used to minimize friction between the soil and the model wall surface. After preparing the soil bed, a sand layer of thickness 2 cm is formed, and a seating plate is placed through which a vertical pressure of 10 kPa is applied with the help of a loading bar and kept for seven (7) days. After that, an incremental vertical surcharge pressure of 10 kPa is applied at an interval of 7 days up to 63 days. And, the corresponding consolidation settlements are recorded with the help of dial gauges.

(ii) Tilted PVD. In this case, a PVD is held making an angle of 85°55′ (φ) at the bottom center with the model base, i.e., at an angle of 4°45′ (θ) with the vertical line. It is so obtained by tilting the PVD by a small amount of 5 cm (*x*) length from the model's center point. After forming the sand layer, the same test procedures are followed, just as in the first case. On the other hand, if an eight (8) m long PVD is mistakenly dislocated horizontally during the installation due to defective machinery measures or improper monitoring arrangements, an angle 4°45′ (θ) is formed with the vertical line making 66 cm (*x*) displacement at the ground surface. Taking into account this example, the tilting angle of 4°45′ (θ) was considered in the laboratory study to resemble the same case.

Table 1. Properties of the soil used

Parameters	Test Method	Results
Specific gravity	IS: 2720 (Part 3)–1980	2.59
Natural moisture content (%)	IS: 2720 (Part 2)–1980	82.23
Liquid limit (%)	IS: 2720 (Part 5)–1985	52.20
Plastic limit (%)	IS: 2720 (Part 5)–1985	28.71
Plasticity index (%)	IS: 2720 (Part 5)–1985	16.49
Grain size	IS: 2720 (Part 4)–1985	
Sand (%)		2.82
Silt (%)		44.72
Clay (%)		52.46
Coefficient of consolidation (c_v) (m^2/s)	IS: 2720 (Part 15)–1986	5.65×10^{-8}
Permeability (m/s)	IS: 2720 (Part 17)–1986	
Standard Proctor Test	IS: 2720 (Part 7)–1980	
Optimum moisture content (OMC) (%)		23.65
Maximum dry density (MDD) (g/cm^3)		1.58

Table 2. Properties of the PVD used

Parameters	Test Method	Results
Core material	ASTM D 276	PP
Width (mm)	ASTM D 3774	100.00
Thickness (mm)	ASTM D 5199	4.00
Width-width tensile strength (kN/m)	ASTM D 4595	≥ 7.00
Tensile strength (kN/m)	ASTM D 4595 EN ISO 10319	≥ 2.50
Elongation at 0.5 kN (%)	ASTM D 4595 EN ISO 10319	≤ 10
Discharge capacity, 300 kPa (i=1) (cm^3/s)	ASTM D 4716	≥ 100
Permeability (cm/s)	ASTM D 4491	$\geq 1.4\times10^{-4}$
Permittivity (s^{-1})	ASTM D 4491	0.44
Apparent opening size, O_{90} (μ)	EN ISO 12956	< 85

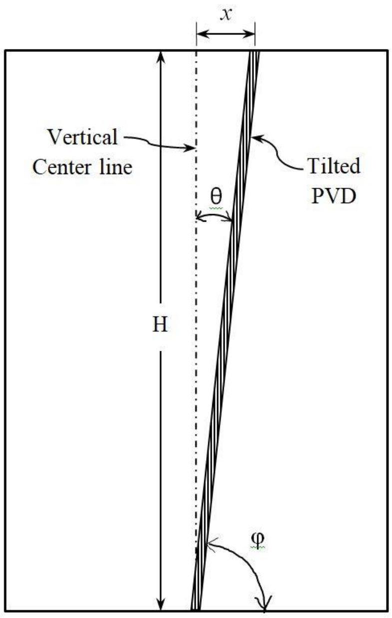

Fig. 1. Tilting of a PVD of height 'H' at an angle 'θ' with the vertical line, making an angle 'φ' with the base line and a horizontal displacement '*x*' at top surface

4 Results and Discussions

4.1 Consolidation of vertical PVD treated soil

In this case, there is no dislocation of the PVD at the top surface, i.e., the PVD is vertically straight, hence $x = 0$. When the soil is treated with the PVD by keeping it vertical, the consolidation settlement rate is very high within 35 days of superimposing the load. At the same time, the total vertical pressure reaches to 50 kPa. A steep curve is observed within this period that implies large settlements of the soil. The reason is the quick horizontal movement of excess pore water within days. After 35 days, the consolidation settlement started decreasing and gives the result as 27.80 mm. The reason is clogging occurring in opening pores of the PVD by soil particles and buckling at the top portion, which significantly affects the discharge capacity. Crimping, folding, bending, kinking, or buckling may reduce the discharge capacity, hence settlement, significantly or even completely (Tran-Nyugen et al. 2010). The magnitude of clogging never decreases but increases with time. Due to this phenomenon, the consolidation rate gradually decreases after this point and almost becomes constant, showing the settlement result as 29.40 mm after 63 days, even though the total pressure now is 90 kPa. It is presumed that the settlement value could have been more if the incremental loading rate is more than 10 kPa.

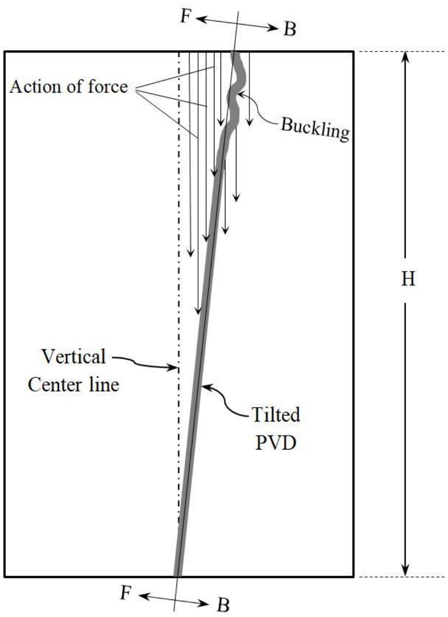

Fig. 2. Action of vertical force on front face (F) and back face (B) of the tilted PVD

4.2 Consolidation of tilted PVD treated soil

Here, the PVD is dislocated at the top surface from the center point by 5 cm, i.e., x = 5 cm. After imposing the vertical pressure, the consolidation settlement rate is very high at the beginning period between 1 to 21 days, and a very steep curve can be seen (Fig.3). But, after this point, this rate gradually starts decreasing, and the settlement becomes 22.60 mm after 21 days. It may be attributed to the extreme clogging and buckling at the top portion of the PVD. Fig. 2 shows the distribution of action of vertical force on two faces (assumed); front face (F) and back face (B). In this case, since the PVD is tilted, the PVD's front face encounters more pressure as the force is acting vertically due to which clogging expedites in this face compared to another face (back side). However, fewer folds in the buckling portion are observed than the first case (vertical PVD treated soil). These are the reasons the tilted PVD treated soil exhibits less consolidation settlement than vertical PVD treated soil. After 63 days, the consolidation result is observed as 24.60 mm.

4.3 Comparison of the results

Consolidation settlement results are compared and shown in Fig. 3. From this figure, it can be seen that untreated soil has the lowest consolidation settlements, and more consolidation settlements are observed in the case of vertical PVD treated soil. But, at the beginning stage, a comparative steep curve is observed (between 1 to 24 days) in tilted PVD-treated soil. It gradually decreases and tends to be almost constant after 42 days producing 29.40 mm and 24.60 mm settlements for vertically PVD treated soil after 63 days. Therefore, the deviation in the result is 4.80 mm. In other words, if the verticality of the PVD is changed, there must be some deviation in the consolidation results. This deviation even may be more significant if the vertical pressure is changed to a higher magnitude.

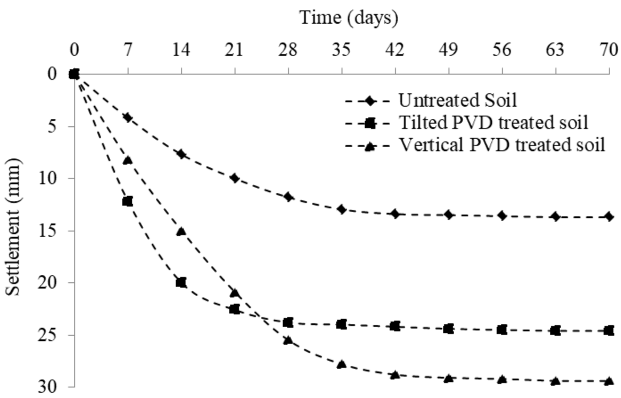

Fig. 3. Comparison of the consolidation settlement results

5 Conclusions

Based on the study made above, the following points may be obtained

1. Consolidation settlement of an untreated soil increase if the soil is treated with PVDs.
2. Tilted PVD expedites settlement of the soil in the beginning periods only; it does not give ultimate expected results.
3. Tilting of the PVD significantly affects on the consolidation settlement. So, it may be concluded that the verticality of PVDs is also an important issue, and great care

should be taken care of during installation in fields. Keeping it as right-angled with the horizontal datum line gives significant results.

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