Investigation on Some Factors Affecting Discharge Capacity of Prefabricated Vertical Drain

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ABSTRACT: A series of laboratory tests have been conducted to investigate the effects of (a) trapped air bubbles in drainage path, (b) folding (no kinking) of drain, (c) confining drain by clay, and (d) elapsed time (long term), on discharge capacity of prefabricated vertical drain (PVD). The test results indicate that confining the drain by rubber membrane yielded a much higher discharge capacity than that in clay. It suggests that the discharge capacity test of PVD should be conducted by confining the drain in clay. Also, the discharge capacity reduces significantly with elapsed time, and the long term behavior of PVD should be considered in design. For most commercially available PVDs, a long term discharge capacity of less than 100 m³/year is tentatively suggested for design. The possible air bubbles trapped in the drainage path of PVD has some influence on discharge capacity, and the test data from this study showed about 20% reduction due to this factor. The folding of the drain does not have obvious influence on discharge capacity because it does not change both length and cross sectional area of drainage path much.

KEYWORDS: Prefabricated vertical drain, Laboratory test, Hydraulic conductivity, Drainage.

1 INTRODUCTION

Installing the vertical drain into ground can shorten the drainage length of the deposit significantly, and with some surcharge loading, the engineering properties, in terms of the compressibility and undrained shear strength, of the deposit can be substantially improved. The development of prefabricated vertical drain (PVD) has made this method more attractive due to the portability of the material and lower installation cost. During past few decades, vertical drain improvement has been widely used in soft soil engineering.

For a given soil condition, the behavior of vertical drain improved subsoil is controlled by: (a) drain spacing and drain diameter, (b) smear effect, and (c) discharge capacity of drain (well resistance). The drain spacing is a known factor and the equivalent drain diameter of PVD can be reliably calculated based on the geometry of the PVD. However, smear effect and discharge capacity have to be determined experimentally. At present, the method for determining the discharge capacity of PVD has not been standardized, and the values reported in the literature are not consistent. Most test methods confine the drain by rubber membrane, such as ASTM D4716-87, and determined values are usually high. However, some low values were reported for confining the drain in clay (e.g. Hansbo 1983). An ideal discharge capacity test should simulate the drain installation, confinement of clay on the filter sleeve of drain, and the deformation of drain during consolidation. It is obvious that a full scale test could be expensive if it is possible. For a small scale laboratory test to be valid, it must consider the important influence factors. In order to improve the laboratory test method and advance the prediction ability on the behavior of vertical drain improved

subsoil, there is a need to investigate the main influencing factors on discharge capacity of PVD.

In this paper, the effect of (a) possible air bubbles trapped in the drainage path, (b) folding (no kinking) of drain which most likely will occur in the field due to consolidation of soil, (c) confining the drain by clay, and (d) elapsed time (long term) on discharge capacity of PVD are systematically investigated. First, the unit cell (a drain surrounded by a soil cylinder) consolidation theory is briefly reviewed to indicate the effect of discharge capacity on the rate of consolidation. Then the laboratory test methods as well as results are presented. The suggestions are made on improving the test method on discharge capacity of PVD.

2 A BRIEF REVIEW ON UNIT CELL THEORY

The basic theory of vertical drain consolidation is unit cell theory which was first proposed by Barron (1948). Further studies on unit cell behavior were made by Yoshikuni and Nakanodo (1974) and Hansbo (1981). Since Hansbo's theory is relatively simple, it has been widely used. The derivation of the theory is based on equal vertical strain assumption. The resulting equation for average degree of radial consolidation (υr) of a unit cell is as follows:

\[ \overline{u_r} = 1 - \exp(-8T_h/\mu) \]  (1)

\[ T_h = \frac{C_h t}{D^2} \]  (2)

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\[ \mu = \ln \frac{n}{s} + \frac{k_h}{k_s} \ln s - \frac{3}{4} + \pi \frac{21^2 k_h}{3q_w} \]  \hspace{1cm} (3)

Where \( C_h \) is the horizontal coefficient of consolidation, \( t \) is time, \( D \) is the diameter of unit cell, \( k_h \) is the horizontal permeability of soil, \( k_s \) is permeability in smear zone, \( l \) is drainage length, \( q_w \) is discharge capacity, \( n=\frac{D}{d_w} \), and \( s=d_h/d_w \) (\( d_w \) is the diameter of drain, and \( d_h \) is the diameter of smear zone). The last term in Equation 3 represents the well resistance. It can be seen that the larger the discharge capacity, \( q_w \), the smaller the well resistance, and the higher the rate of consolidation. For example, assuming \( l=15 \) m and \( k_h=10^{-8} \) m/sec, if \( q_w \) is less than 100 m\(^3\)year, it will have a considerable influence on consolidation rate of vertical drain improved subsoil.

3 APPARATUS AND TEST METHODS

3.1 Apparatus and Test Procedure

The apparatus used is a modified triaxial device as shown in Figure 1. The main cell has a diameter of 200 mm and height of 600 mm. The drain sample is set inside the cell similar to that of setting the triaxial test sample. The lower pedestal is fixed at the bottom of the cell and connected to the inlet water flow system. The upper pedestal is movable (for adjusting the length of drain sample) and connected to the outlet water flow system. The drain length can be tested is 200 mm to 400 mm. The shape of pedestal is made as: one end is cylindrical for fixing the membrane, and rectangular at another end to connect the drain. In this way, when confining the drain by rubber membrane, there will be no gap between membrane and drain. The length of drain inserted into the slot of upper and lower pedestal is about 30 mm each. The diameter of the pedestal is 100 mm. Except the main cell, there are inlet and outlet water containers. The inlet water container is linked with water supply system, and outlet water container is connected to discharge capacity measuring device. After the drain is installed, the cell is filled with water up to about 80% full, and confining pressure is applied by air pressure through an air pressure regulator. For investigating the effect of folding, the drain is folded at one and two point for 10% and 20% vertical strain, respectively. The methods for investigating the possible trapped air bubble effect and confining the drain by clay are described as follows.

3.2 Method for Investigating the Effect of Trapped Air Bubbles

It is considered that installing a drain into ground, the water from soil gradually enters the drain along the whole length of the drain, and there might be some air bubbles trapped into drainage channels. In order to study the possible trapped air bubble effect, a simple air bubble generation device is newly developed. A thin plastic tube is connected to an air tank through an air pressure regulator. Then the tube is placed at the bottom of the drain sample through an inlet hose as shown in Figure 2. The amount of air bubbles generated can be controlled by adjusting the air pressure regulator. The generated air bubbles enter the drain following the water flow. The main test steps are:

1. Set-up the drain sample and apply the desired confining pressure as well as hydraulic gradient.

2. Generate the air bubbles with a diameter of about 1 mm, and a speed of about 100 bubble/min. This process is continued for about 4-6 hours.

Figure 1. Set-up of discharge capacity test apparatus

Figure 2. Method for generating air bubbles
(3) Close the air bubble generation system, and let the water flow continue for more than 2 hours to steady the flow. Then measure the discharge capacity.

3.3 Test Procedure for Confining the Drain by Clay

Hansbo (1983) recognized the importance of confining the drain by clay on determining the discharge capacity. However, due to convenience, most discharge capacity tests conducted by manufacturers are confining the drain by rubber membrane. One of the purposes of this investigation is to compare the discharge capacities determined by clay confinement and membrane confinement. The test method proposed in this study for testing the drain in clay is simple and can test the full size of drain. The following main steps are followed during test:

(1) Connect the drain sample to lower pedestal, fix the membrane to lower pedestal also, and set the mould for preparing the clay sample in position.

(2) Make clay sample. The remoulded clay with a water content close to the liquid limit is put into the mould layer by layer keeping the drain in the middle. The diameter of the clay sample is 100 mm. After the required height of clay sample is reached, the upper pedestal is installed and the drain is connected to outlet flow system. Care needs to be paid to prevent the contamination of the top of drain by clay.

(3) Consolidate the clay sample. For removing the mould, a suction of about 10 kPa is applied to the clay sample. After confining pressure is applied, the suction is gradually released and the sample is left for consolidation under lateral pressure.

(4) Measure discharge capacity. After the consolidation of clay sample is finished, the discharge capacity is measured under desired hydraulic gradient.

The set-up of the drain confined by clay is illustrated in Figure 3. With this method, a test with one consolidation pressure and several hydraulic gradients requires 10 days to complete.

3.4 Considering the Head Loss in Hose System

Another factor which has been noticed during the investigation is head loss in the hose of the test equipment. Since the discharge capacity of drain confined in membrane is normally high, ignoring the head loss in the hose does not introduce much error. For testing the drain in clay, which is close to field condition, the head loss in the testing system needs to be considered. The calibration of the head loss in the hose system can be made by conducting the test without installing a drain sample.

4 TEST RESULTS AND DISCUSSIONS

4.1 Materials Used

The PVD adopted in this study is a commercial product and its properties are summarized in Table 1. The soil used is remoulded Ariake clay. Its index properties are: specific gravity, $p_s$, of 2.60, plastic limit, $w_p$, of 42.8%, and liquid limit, $w_l$, of 105.0%. The soil consists of 57.0% clay, 41.7% silt, and 1.3% sand particles. The rubber membrane used has a thickness of 1.0 mm.

<table>
<thead>
<tr>
<th>Table 1: Physical properties of PVD</th>
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<tr>
<td>Size (mm)</td>
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<tr>
<td>Drainage channel Depth(mm)</td>
</tr>
<tr>
<td>Width(mm)</td>
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<tr>
<td>No. of channel/drain</td>
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<tr>
<td>Unit weight (g/m)</td>
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<td>Material Filter</td>
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<tr>
<td>Core</td>
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<tr>
<td>Connection condition between filter and core</td>
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<td>Structure</td>
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4.2 Short Term Test Results

For ease in quantifying each influencing factor, the test results of confining a straight drain in a rubber membrane are considered as basic ones and other test results are compared with them. The confining pressures for the basic test were 49 and 392 kPa, and hydraulic gradients were 1998 Sixth International Conference on Geosynthetics - 847
(1) Confining the drain by a rubber membrane can not simulate the actual field condition and the discharge capacity test for determining the design value should confine the drain with clay. When confined by a rubber membrane, it results in a much higher discharge capacity than that in clay. For the case investigated, the clay value is only about 20% of membrane value. Three possible reasons for reduction on discharge capacity of PVD in clay can be considered.

(a) Reducing the cross sectional area of drainage channel due to deformation of filter under pressure. This has been considered as the main reason. After the test, it was observed that the filter was considerably deformed and the cross sectional area of drainage channel was reduced to 70-50% of original value as shown in Figure 6. The left side of Figure 6 was made by stamping the actually used soil sample on paper. Since the amount of reduction on cross-sectional area is a function of stiffness of filter, as a supplementary information, the tension force versus tension strain relationship of the filter was determined by the laboratory wide strip test, with a strain rate of about 1%/min as shown in Figure 7. For the case of confined in rubber membrane, due to the tension stiffness of membrane, filter can not deform as freely as that in clay.

(b) Reducing the conductivity of filter in longitudinal direction due to soil particles penetrating into the opening of filter. When confining the drain in rubber membrane, the filter may act as a part of vertical water flow path. In the case of confined by clay, the clay particles will enter the opening of the filter and reduce the conductivity of filter. Since the thickness

Figure 4. Results of basic test

about 0.08 and 0.8. The results are plotted in Figure 4. It can be seen that as a general tendency the discharge capacity is reduced with increased confining pressure. It is the same as the results reported in the literature (e.g. Hansbo 1987). If extrapolating the results to unit hydraulic gradient (i=1.0), a discharge capacity of 1981 m³/year and 1307 m³/year can be obtained for confining pressures of 49 kPa and 392 kPa, respectively. The short term test results are summarized in Figure 5. A discharge capacity ratio is used in the figure, which is defined as the amount of water flow, Q, divided by the corresponding value of basic test, Q₀ (Q/Q₀). Following discussions can be made for short term test results.

Figure 5. Summary of short term test results

(b) Reducing the conductivity of filter in longitudinal direction due to soil particles penetrating into the opening of filter. When confining the drain in rubber membrane, the filter may act as a part of vertical water flow path. In the case of confined by clay, the clay particles will enter the opening of the filter and reduce the conductivity of filter. Since the thickness
Stepping on the water flow hose is just like applying pressure pulses to water flow system. It was observed that some flocculated fine particles were pressured (due to stepping) out of the drainage channel of drain and deposited on the wall of the outlet hose. Based on these results, it is considered that the reasons for the reduction of discharge capacity with elapsed time are: (1) creep behavior of filter which reduces the cross-sectional area of drainage path, and (2) clogging caused by flocculated fine particles. As shown in Figure 8, for the case investigated, the creep effect is evaluated as the difference between last measurement point and the reading at about 1 week of elapsed time, which reduced the discharge capacity about 30%. The most reduction can be attributed to the clogging effect which is a function of soil type and filter type. The chemical analysis about the flocculated fine particles as well as the clay mineral is going on and the results will be reported in the future. The discharge capacity reduction with elapsed time was also reported by Koda et al. (1986) for confining the Geodrain in organic soils. For a drain, it is normally expected to work at least half a year. Therefore, in design, long term behavior of drain should be taken into account.

4.4 Discussions

From this investigation, it shows that the most important factors affecting the discharge capacity of PVD are: (a) confining condition, and (b) the duration of test. Therefore, for determining the design value of discharge capacity, the test should be conducted by confining the drain by clay and tested for a longer period (may be few month). If comparing the results from this study with those reported in the literatures, the following comments can be made.

4.3 Long Term Test Results

Only one test of confining the drain in clay was tested for about 5 months. The conditions were: confining pressure of 49 kPa and hydraulic gradient of 0.08. This confining pressure approximately represents the lateral earth pressure in subsoil under a 5 m high embankment or at 10 to 15 m depth of natural subsoil. A lower hydraulic gradient is adopted because, in the field, the average value during consolidation process may not be high. The long term test results are shown in Figure 8, which indicate that the discharge capacity was continuously reduced with elapsed time except the last measurement point. It has been understood that in the interval between the last two measurements, the inlet hose (about 30 mm in diameter and flexible) had been stepped on several times unexpectedly.

Figure 7. Tensile force versus tensile strain curve for filter

of the filter is only about 0.2 mm, this effect is a minor one.

(c) Clay particles enter the drainage channel. Although the most of filters commercially used satisfy the filtration criteria, the experimental evidence indicates that some amount of very fine particles entered the drainage path and forming loose flocculated sediments on the wall of drainage path. It is considered that the formation of the flocculated sediments is a function of chemical contents of clay.

(2) It seems that not much air bubbles can remain in the drainage path. The data from this study show that the trapped air bubbles reduced the discharge capacity about 20%.

(3) Considering a vertical strain up to 20%, the folding of the drain has minimal effect on discharge capacity, which supports the conclusion drawn by Hansbo (1983). This factor can be explained as the folding of the drain does not change both the length and cross-sectional area of drainage path much. The kinking was not considered in this study because it rarely occurs in the field.

Figure 8. Long term discharge capacity test results

(1) The values of confining the drain by rubber membrane are comparable with the data reported by manufacturers. Due to the apparent high discharge capacity, it may be considered that the well resistance of PVD can be
ignored in design. However, the results of this study suggest that the high value for confining the drain by rubber membrane may not represent the field condition, and well resistance may be an important design factor, especially for long drains. The discharge capacity of confining the drain by rubber membrane may only be used as a quality control test.

2. In clay short term (about 1 week) value of discharge capacity is in the lower range of the data summarized by Hansbo (1987). Comparing with the specifications about required discharge capacity as summarized by Bergado et al. (1996), it can be seen that with a discharge capacity of fewer hundreds m\(^3\)/year, the most specifications can be satisfied. However, the most specifications have no clear requirement about long term behavior.

3. The long term in clay value (about 5 months) from this study is higher than the data reported by Hansbo (1983) by using the revised CTH (Chalmers University of Technology) method for the similar drain. The revised CTH method also confined the drain in clay with a test duration of less than 1 month. Whether the CTH method considered the head loss in the hose system is not clear, and if not, it might be the reason for the lower value of discharge capacity. The relative lower value of discharge capacity of PVD was also reported by Jamiołkowski et al. (1983). The field discharge capacity may vary with the type of drain, type of clay, and designed consolidation period, but as a rough reference, it is recommended that for most commercial PVD, a design discharge capacity of less than 100 m\(^3\)/year can be used.

5 CONCLUSIONS

Four influence factors on discharge capacity of PVD are experimentally investigated. These factors are: (a) possible trapped air bubbles in drainage path, (b) folding of drain, (c) confining the drain by clay, and (d) long term behavior. From the test results, following conclusions can be drawn:

1. The discharge capacity of PVD confined in clay is significantly lower than that confined by rubber membrane. It is strongly recommended that for determining the design value, the discharge capacity test should be conducted by confining the drain in clay. The test of confining the drain by rubber membrane not represents the field condition and it might be used for quality control purpose only.

2. The discharge capacity of PVD reduces significantly with elapsed time. For the case investigated, the long term minimum value is only about 10% of the value at 1 week. This indicates that for design vertical drain improvement, long term behavior of PVD should be considered. For most commercial PVD, a design long term discharge capacity of less than 100 m\(^3\)/year is tentatively suggested.

3. The possible air bubbles trapped in drainage channel has an effect on discharge capacity. For the case investigated, it shows that the discharge capacity was reduced by about 20% due to the effect of trapped air bubbles.

4. The folding of drain does not influence discharge capacity significantly because it does not change both the length and cross sectional area of drainage path much.

REFERENCES


