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Laboratory measurements of factors affecting discharge capacity of prefabricated vertical drain materials

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Abstract

The discharge capacity is a critical parameter controlling the performance of Prefabricated Vertical Drains (PVDs). The laboratory measurement of the discharge capacity is of the upmost importance when it comes to assessing the performance of proposed PVDs prior to their usage in the field, and hence, the significance of this paper. However, the laboratory measurement of the discharge capacity required to obtain the optimal performance of PVDs by laboratory testing methods is still uncertain. This is because there are various apparatus for discharge capacity testing currently in use by various commercial and research organizations, all of which provide widely varying values of discharge capacity for the same type of PVD under the same hydraulic conditions. The measured discharge capacity of PVDs in the laboratory, with and without surrounding soils, is affected by factors such as the dimensions of the apparatus, the test duration, the hydraulic gradient, the type of surrounding materials, the applied confining pressure and the deformation configuration of the vertical drains. The effects of these factors are investigated, reviewed and discussed in this paper. The relevant equations for obtaining the required discharge capacity of PVDs by laboratory methods are also presented and discussed in this paper. The test results indicate that a small tester results in the underestimation of the discharge capacity particularly for PVDs with a high discharge capacity. A reduction in PVD thickness, the clogging of the filter, the deformation of the PVDs, due to an increase in the duration of the tests (creep), and vertical pressure all cause a reduction in the discharge capacity for a particular hydraulic gradient. Softer surrounding soils and lower PVD stiffness cause a large deformation of the soils surrounding the PVDs. For a particular PVD, the creep effect on the decrease in discharge capacity is significant with a short duration, but becomes insignificant after a long duration. The deformation of PVDs under folded conditions is found to be the most critical factor in the resulting decrease in discharge capacity.

1. Introduction

Prefabricated Vertical Drains (PVDs) are increasingly being used in various ground-improvement projects on soft soil deposits such as marine clay (Bo et al., 2013; Arulrajah et al., 2009; and Bergado et al., 2003a, 2003b) and ultra-soft soil (Bo et al., 2011; Chu et al., 2006, 2009; Ma et al., 2011). In land reclamation and ground-improvement works, PVDs are extensively used (Arulrajah et al., 2004a; Bo et al., 2012; Chu et al., 2005) in combination with either surcharge preloading (Arulrajah et al., 2004b, 2013; Indraratna et al., 2005; Wu et al., 2015) or vacuum preloading (Indraratna and Redana, 1998; Indraratna et al., 2004; Cholachat et al., 2007; Indraratna et al., 2011). The use of PVDs alone and the use of them with

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copper and carbon electrodes can accelerate the consolidation process in soft soil deposits (Chai and Miura, 1999; Bergado et al., 2003a, 2003b; Chai and Cater, 2011). Shen et al. (2005) compared the performance of full-scale embankments on soft soil deposits with and without PVD installation. They reported that the equivalent vertical permeability for an embankment with PVD installation was 30 times higher than that without PVD installation.

The discharge capacity is a critical parameter that controls the design and performance of PVDs (Bo et al., 2007; Sharma and Xiao, 2000; Rawes, 1997; Sprague, 1995) and can be determined in a laboratory (Bergado et al., 1996). Only PVDs that have sufficient discharge capacity can function satisfactorily (Bo, 2004). There are many factors affecting the discharge capacity in the field (Arulrajah et al., 2005; Arulrajah et al., 2006; Bo, 2004; Tripathi and Nagesha, 2010), which might lead to inaccurate predictions of the field performance. Indraratna and Redana (2000) introduced an equivalent plane strain model to perform a multi-drain analysis. They reported that the inclusion of the smear effect and a high resistance to the discharge capacity resulted in an improvement in the prediction results. Chai et al. (2004) proposed a method for calculating the hydraulic radius of PVDs by taking the deformation of the filter into account. In addition, the installation of PVDs might result in the unsaturation of the soil adjacent to the PVDs and might affect the pore pressure dissipation (Indraratna et al., 2004).

Although there have been many attempts at assessing the discharge capacity in the field, there has been only very limited work to date in assessing factors that affect the measurement of the discharge capacity by the various laboratory testing methods. The factors that affect the laboratory discharge capacity of PVDs are of critical importance as they are undertaken prior to the selection of proposed PVDs for usage in the field.

ASTM (2008) is usually adopted in the determination of constant head hydraulic transitivity (in-plane flow) in the laboratory for geotextile products. In this test method, the discharge capacity of the PVDs can be obtained indirectly. More specific and relevant methods have been proposed by Ali (1991), Bergado et al. (1996), Chu and Choa (1995), Kamon et al. (1994) and Miura et al. (1993) with the use of various apparatus for the measurement of the discharge capacity of PVDs. However, the various apparatus and testing methods yield different values of discharge capacity. This paper discusses the determination of the required discharge capacity of PVDs and the factors that affect the testing results when using these various laboratory testing apparatus.

2. Definition of discharge capacity

Discharge capacity is defined as the rate of water flow per unit of hydraulic gradient.

$$q_w = \frac{Q}{i} = Qdl/dh \tag{1}$$

where q_w is the rate of water flow per unit of hydraulic gradient in m^3/s, Q is the average quantity of water discharge per unit of time (m^3/s), i is the dimensionless hydraulic gradient, l is flow length and h is water head (meters). Since the discharge capacity is dependent on the water flow rate, it is measured under a temperature of 20 °C (68 °F).

3. Determination of required discharge capacity

The required discharge capacity was proposed by Mesri and Lo (1991) as five times the discharge factor (D) based on back analysis data from three major embankment projects. The discharge factor is defined as

$$D = \frac{q_w}{\left(k_h l_m^2\right)} \tag{2}$$

Therefore, the required discharge capacity is $q_w = 5k_h l_m^2$, where k_h is the horizontal permeability of soil and l_m is the maximum drainage length. For most clays, the required discharge capacity varies from 2 to 80 m^3/yr. Kamon et al. (1994) defined the required discharge capacity for PVDs as follows:

$$q_{w(req)} = \frac{0.25 \times 0.1\pi F_s H C_h}{4T_h} \tag{3}$$

where $q_{w(req)}$ is the required discharge capacity in cm^3/day, F_s is the reduction factor, T_h is the dimensionless time factor for radial drainage, C_h is the horizontal coefficient of consolidation in cm^2/day and H is the length of the PVDs in cm.

Since consolidation involves the dissipation of water, the total amount of water dissipated is dependent on the compressibility and the thickness of the soil. Den Hoeot (1981) stated that the required discharge capacity for a 100-mm-wide drain should be at least 3×10^{-6} m^3/s based on the allowable settlement of 40 mm/day for a 30-m-long drain. Holtz et al. (1991) recommended that the q_w be between 3×10^{-6} and 9×10^{-6} m^3/s under pressure of 300 to 500 kPa. Karunaratne (2011) suggested that the determination of the discharge capacity of a PVD should be conducted under the maximum magnitude of lateral pressure expected in the field.

A summary of the discharge capacity, specified in a number of soil improvement projects, is presented in Table 1. It is evident that the specified discharge capacity ranges from 5 to 100 ($\times 10^{-6}$) m^3/s under a straight condition and from 6.3 to 32.5 ($\times 10^{-6}$) m^3/s under a buckled condition. Various core configurations for various types of vertical drains are shown in Table 2. As a rule of thumb, the total volume of water to be discharged can be estimated using the following equation:

$$Q_v = \pi H \varepsilon_v \left(D_e/2\right)^2 \tag{4}$$

where Q_v is the volume of the water drained out from the soil in m^3, H is the thickness of the soil in meters, ε_v is the volumetric strain and D_e is the equivalent diameter of the drain in meters. If the time to complete the primary consolidation is known, the average flow rate, Q, can be calculated as

$$Q = Q_v/t \tag{5}$$

The initial hydraulic gradient can be estimated using the initial excess pore pressure and the vertical drain length.

Eq. (6) gives the requirement for the average required discharge capacity. Since the rate of settlement varies during the consolidation process, the rate of flow is faster in the earlier stages and slower in the later stages.

$$q_w = \frac{QL\gamma_w}{\Delta\delta'} = \frac{\pi H \varepsilon_v L \gamma_w \left(D_e/2\right)^2}{\Delta\delta' t} \tag{6}$$

where L is length of the PVD in meters, $\Delta\delta'$ is the additional effective load (kPa) and γ_w is the density of water (kN/m^3).

Table 1
Comparison of discharge capacity specified in various international projects.

Country		Straight condition		Buckled condition	
		Discharge capacity ($m^3/s \times 10^{-6}$)	**Test condition**	**Discharge capacity ($m^3/s \times 10^{-6}$)**	**Test condition**
Netherlands	<10 m thick	>10	350 kPa, 30 days	>7.5	350 kPa
	>10 m	>50	350 kPa, 30 days, i = 1	>32.5	350 kPa, 30 days
Singapore		>25	350 kPa, 28 days	>10	
Thailand		>16	200 kPa, 7 days, i = 1		
Hong Kong		>5	200 kPa		
Malaysia		>6.3	400 kPa, i = 1	>6.3	400 kPa, 40 m
Australia		>100	300 kPa		
Finland		>10			
Greece		>10	100 kPa		

Table 2
Core configurations in tested PVDs.

Type	Core configuration	Remark
A	Wire-mesh core	
B1	Corrugated core	Same type of drain manufactured in different countries.
B2	Corrugated core	
B3	Corrugated core	
C	Corrugated core	
D	Box channel	

4. Factors affecting measurements of discharge capacity

In order to determine the various factors affecting the measurements of discharge capacity of PVDs, four main types of drains, namely, Types A, B, C and D, were selected in this study. All the drains, except Type D, were tested in the laboratory using the apparatus described in this section. The Type D drain was tested at the Asia Institute of Technology and the results were reported by Bergado et al. (1996). The physical and mechanical properties of the Types A, B and C drains are shown in Table 3, while their cross sections are shown in Fig. 1.

Two types of testing apparatus, the straight drain tester, developed by Broms et al. (1994) and Chu and Choa (1995), and the buckled drain tester, developed at Nanyang Technological University in Singapore, were used in the study. The straight drain tester was designed to comply with ASTM 4716, but with the necessary modifications. Testers with two different dimensions, 100 mm × 100 mm and 100 mm × 300 mm, were used. The cross section of the straight drain tester is shown in Fig. 2. The inflow and the outflow of water were conducted through the side of the two ends of the testers with which the core of the drain was aligned. Vertical pressure was applied using an oedometer frame. Details of the apparatus can be found in Bo et al. (2003). The buckled drain tester, shown in Fig. 3, was used to test the discharge capacity of the deformed drains. This tester was designed with an inner diameter of 150 mm to accommodate a 400-mm-long drain

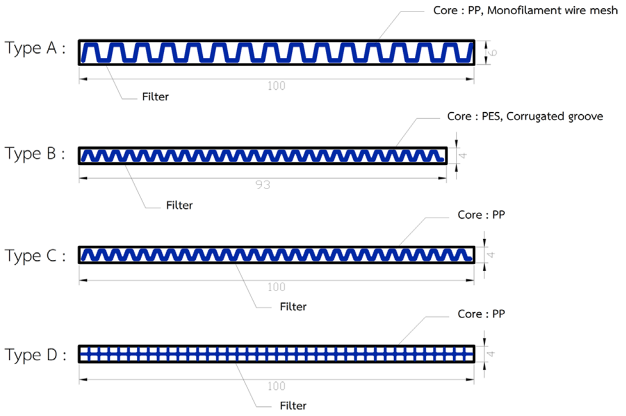

Fig. 1. Cross sections of Type A drain (top) and Types B and C drains (bottom).

Table 3
Physical and mechanical properties of tested drains.

	Type A	Type B	Type C	Type D
Core material	PP, monofilament wire mesh	PES, corrugated groove	PP	PES, corrugated groove
Filter material	PP, needle punched nonwoven fabric	PES, nonwoven fabric	PP	PES, nonwoven fabric
Dimensions (mm)	100 × 6	93 × 4	100 × 4	98 × 4
Weight (g/m)	70	89	90	91
Tensile strength (kN)	1.8	3.5	2	3
Elongation (%)	22.5	35	50	40
Pore size (μm)	85 for O_{95}	75 for O_{95}	75 for O_{95}	75 for O_{95}

Note: PP = Polypropylene PES= Polyester.

sample. The cylinder, with a drain specimen in the center, was filled with reconstituted clay. The clay was consolidated with compressed air via a piston. The inflow of water was applied from the bottom and the outflow was applied from the top through the piston. During consolidation, the drain buckled inside the clay. PVDs can be tested under deformed linear strain of between 20% and 50%. The kinked drain tester, measuring 300 mm by 100 mm, modified the sample to be tested in the straight drain tester, as shown in Fig. 4, and was used to investigate the discharge capacity of deformed Type D drains.

4.1. Types of apparatus

As explained earlier, there are various types of discharge capacity testing equipment. However, the rate of discharge is

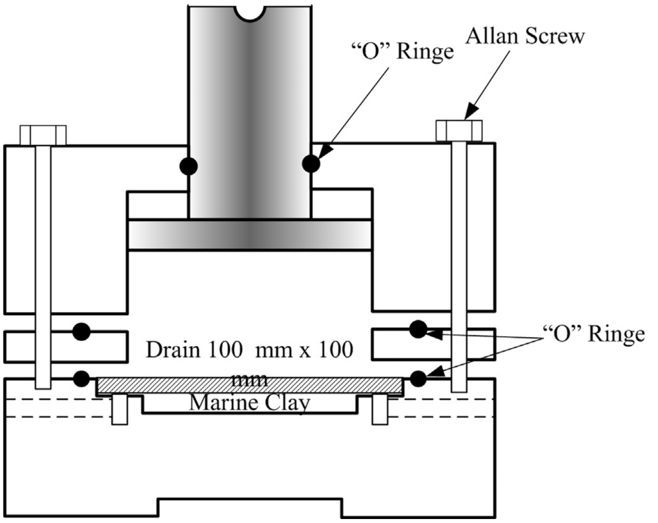

Fig. 2. Cross section of the straight drain tester.

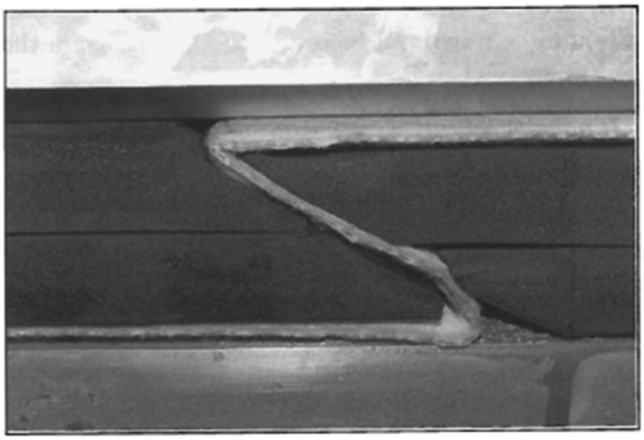

Fig. 4. Kinked drain tester.

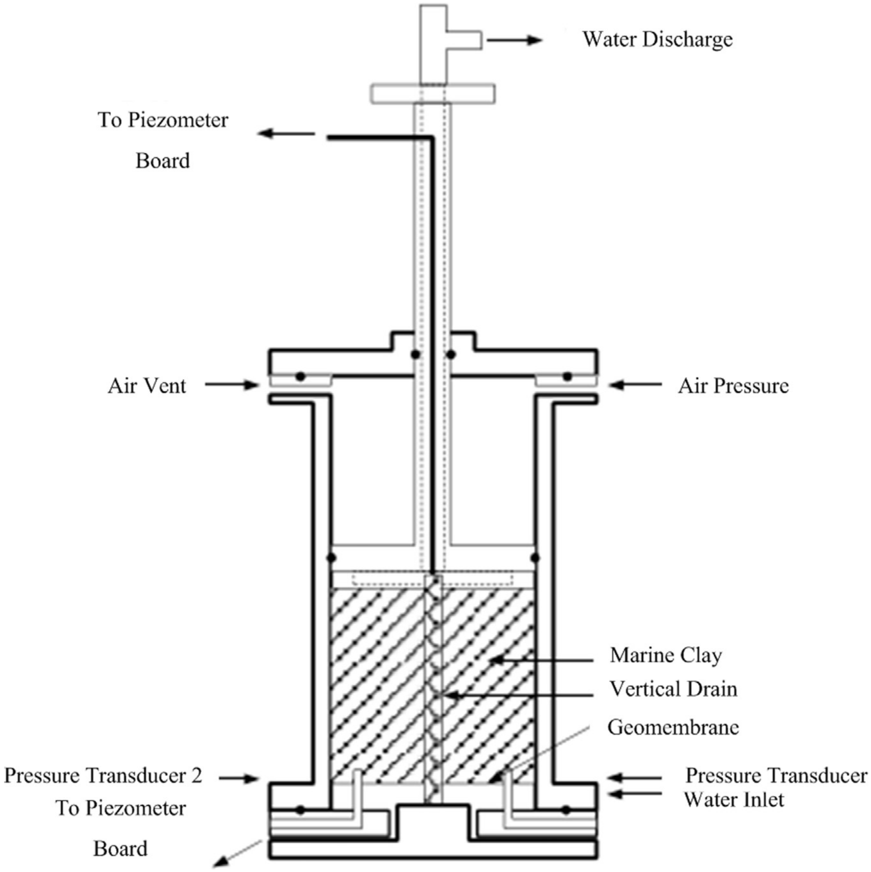

Fig. 3. Buckled drain tester.

calculated based on Darcy's law as

$$Q = kiA = k\frac{dh}{dL}A \tag{7}$$

As long as the hydraulic gradient is constant, the rate of discharge will also be constant for flow media having constant permeability and cross sections, regardless of the magnitude of the head (*dh*). However, as observed in some tests, the rate of discharge through the vertical drains increases with the difference in head under the same hydraulic gradient. The discharge capacity measured at the same hydraulic gradient may increase with the length of the PVD tested. In other words, the measurement of the PVD discharge capacity is affected by the dimensions of the apparatus. The variations in discharge capacity with the different dimensions of the apparatus are shown in Fig. 5 for the Type A and Type B drains. It is seen in Fig. 5 that the Type B drain (higher discharge capacity) is most affected by the dimensions of the testing apparatus. This implies that a tester with large dimensions is required for drains with a high discharge capacity because a tester with small dimensions results in the underestimation of the discharge capacity.

Type A drains were also tested under straight and buckled conditions using different types of apparatus, such as ASTM (2008) and Chu and Choa (1995). It was found that the 100 mm by 100 mm tester by Chu and Choa (1995) gave lower discharge capacities compared to the ASTM (2008) apparatus under both straight and buckled conditions, as shown in Fig. 6. The significant difference in discharge capacity between straight and buckled conditions is noted for the PVD tested with the 100 mm by 100 mm tester, while similar test results were obtained for the test using the ASTM (2008) apparatus. These results show the advantage of the 100 mm by 100 mm tester over the ASTM (2008) apparatus in determining the discharge capacity as the cost of the apparatus itself, and the time and the cost to prepare the sample, are much less for the 100 mm by 100 mm tester.

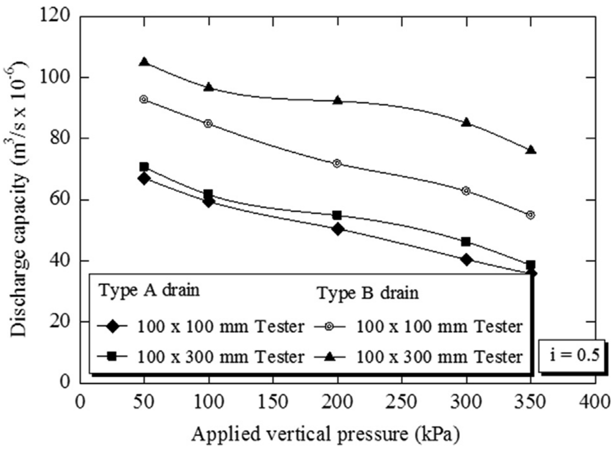

Fig. 5. Variation in discharge capacity due to dimensions of apparatus.

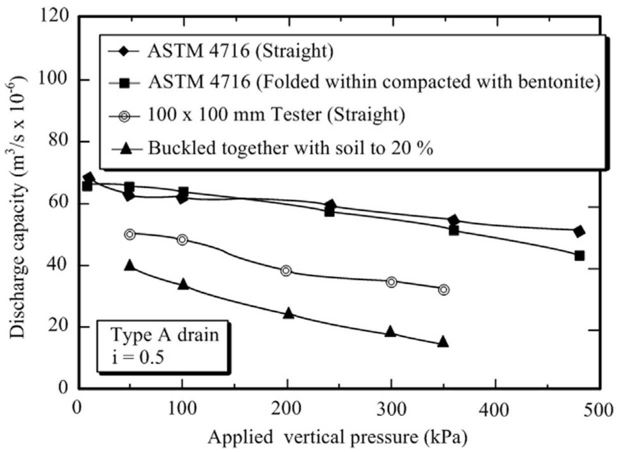

Fig. 6. Variation in discharge capacity resulting from different types of apparatus.

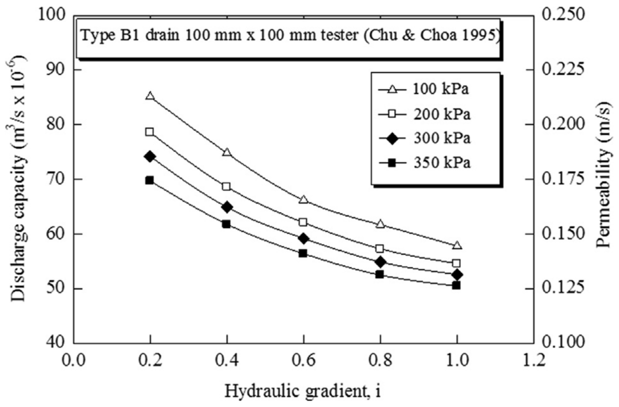

Fig. 7. Decrease in permeability and discharge capacity with hydraulic gradient.

4.2. Hydraulic gradient

In Darcy's Law, the permeability of porous media is assumed constant. Therefore, the discharge capacity in porous media is constant for a area of certain dimensions, although the hydraulic gradient is varied.

However, in a flow through the PVD core, the permeability of the core is not constant. It varies with the hydraulic gradient. It is evident from Fig. 7 that the in-plane permeability of the PVD decreases with an increasing hydraulic gradient and vertical pressure. Hence, the discharge capacity of the PVD decreases with an increasing hydraulic gradient in exponential function. This implies that the flow through the PVD may not follow Darcy's law, which is only applicable for flows through porous media. The decrease in discharge capacity with an increasing hydraulic gradient is significant at small levels of vertical pressure. The decrease in discharge capacity with an increasing vertical pressure is larger for smaller hydraulic gradients.

4.3. Vertical pressure

The thickness of the PVD is reduced with an increasing vertical pressure, as shown in Fig. 8, for Type A and Type B drains under vertical pressure ranging from 0 to 350 kPa.

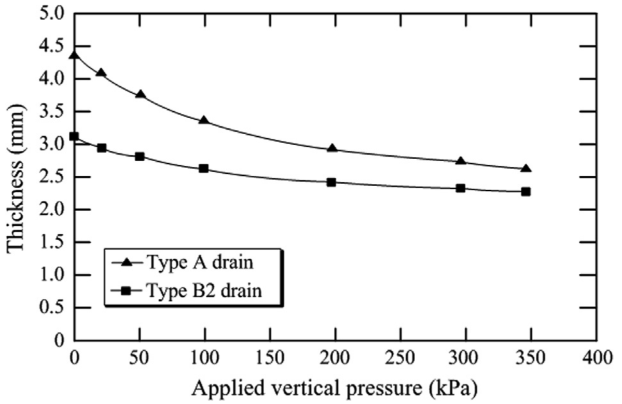

Fig. 8. Decrease in thickness of vertical drains under increasing pressure.

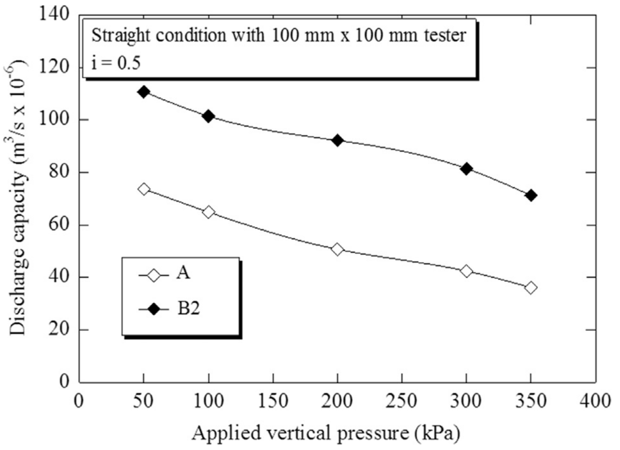

Fig. 9. Decrease in discharge capacity with confining pressure.

The reduction in thickness with vertical pressure can be expressed by an exponential function for both tested drains and the reduction is significant for the Type A drain, which is thicker than the Type B drain. The effect of the initial thickness and the decrease in thickness due to vertical pressure on the discharge capacity is found in Fig. 9, which was tested using the 100 mm by 100 mm tester under the same vertical pressure and hydraulic gradient. The discharge capacity of the Type B drain is evidently higher than that of the Type A drain due to the greater thickness; i.e., the discharge capacity at a vertical pressure of 50 kPa is 155×10^{-6} m^3/s and 73×10^{-6} m^3/s for the Type B drain and the Type A drain, respectively. Kamon et al. (1994) reported that when the PVD was confined at a cell pressure of 320 kPa, the discharge capacity could be reduced by 55% to 90% of that measured at a cell pressure of 5 kPa. However, this decrease in discharge capacity due to vertical or confining pressure varies over a wide range depending upon the type of drain. For this study, the decrease in discharge capacity with an increasing vertical pressure for both tested drains has a similar pattern, which can be represented by a linear function. The discharge capacity at the vertical pressure of 350 kPa for the Type A drain (wire-mesh core) is reduced to about half of the value at the vertical pressure of 50 kPa, while the reduction in discharge capacity for the Type B drain (corrugated core) is slightly lower. The slightly lower decrease in discharge capacity for the Type B drain is possibly due to the slightly lower thickness ratio between the vertical pressure levels of 50 kPa and 350 kPa; i.e., it is 1.21 for the Type B drain and 1.5 for the Type A drain (Fig. 8).

4.4. Duration of test

In addition to the effect of vertical pressure, the cross-sectional area of the PVD under a vertical pressure becomes smaller with time due to creep. The variation in discharge capacity with the duration of the test, measured for the Type A drain using the 100 mm by 100 mm tester, is shown in Fig. 10. The duration of the test addressed in this study is started from the application of confining pressure. For the same hydraulic gradient, the decrease in discharge capacity with the duration of the test is significant and approximately linear for test durations shorter than 8 weeks. The effect of the test duration tends to be insignificant when the duration is longer than 9 weeks, as seen by the minimal difference in the relationship between the discharge capacity and the hydraulic gradient for the 9th and 10th tests.

4.5. Stiffness of surrounding soils and vertical drain

In practice, PVDs are installed in soft clay deposits. Therefore, the discharge capacity of the PVDs needs to be examined under surrounding soil conditions. It is apparent that the different discharge capacity values were obtained when the PVDs were tested using different types of surrounding soil under the same loading and hydraulic gradient. Fig. 11 shows the discharge capacity of the Type A drain surrounded by three types of soil and tested by the straight drain tester (100 mm by 100 mm) under a vertical pressure of 350 kPa and a hydraulic gradient of approximately 0.5. In the figure, immediate loading means loading with one step of 350 kPa, while incremental loading means loading incrementally with a load increment ratio of 1 to reach 350 kPa. Detailed characteristics of the marine clay and the grain size distribution of the sand used here can be found in Bo and Choa (2004). It is evident that softer surrounding soil results in a lower discharge capacity.

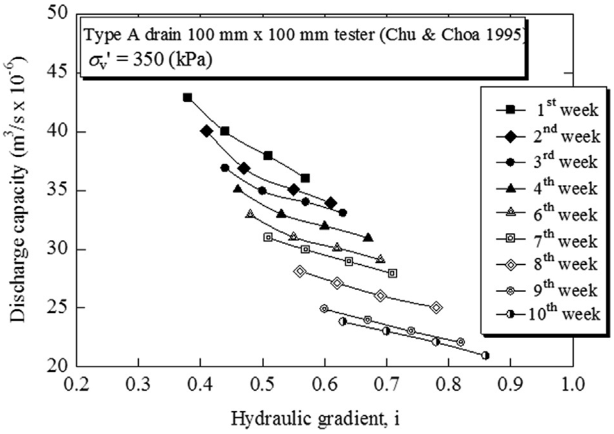

Fig. 10. Decrease in discharge capacity with duration of test.

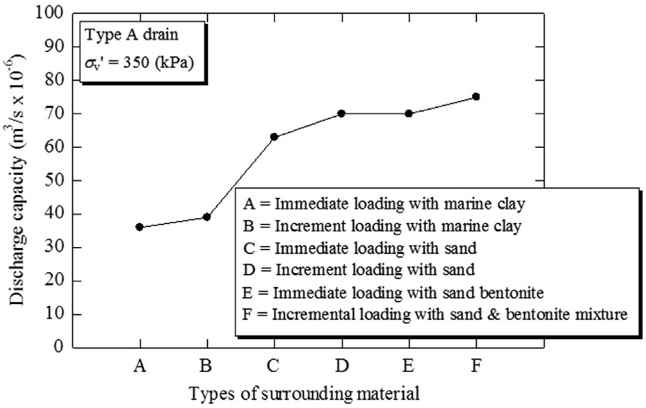

Fig. 11. Variation in discharge capacity due to various types of surrounding materials.

This lower capacity at vertical pressure could be due to various factors, such as: (1) the squeezing of the filter into the channels of the core is significant for low stiff surrounding soil. (2) the filter may be clogged when fine soil is used, and therefore, the flow along the filter is reduced. Basu and Madhav (2000) also reported that some fine materials ingress into the drain during testing and the clogging of the drainage channel becomes apparent. It is found that the discharge capacity under incremental loading is higher than that under immediate loading, possibly because immediate loading causes more squeezing and clogging in the filter.

Discharge capacity tests were also carried out with synthetic surrounding materials, such as geomembranes, to investigate the effect of the stiffness of the drain. The test results are shown in Fig. 12. The stiffness values of the geomembranes are 42.5, 50, 52.5, 56.3 and 68.8 kN/m for geomembrane thicknesses of 0.45, 0.75, 1.00, 1.50 and 2.00 mm, respectively. The tests were undertaken under the same vertical pressure of 350 kPa and hydraulic gradient of 0.5. It is evident that a greater level of stiffness of the drain materials results in a higher respective discharge capacity due to the smaller deformation of the filter and the drainage channel. Chai et al. (2004) calculated hydraulic radius R, defined as the cross-sectional area divided by the perimeter of the drainage channel, using data from drainage capacity tests. They concluded that a stiff filter, a strong core and a large drainage channel can reproduce a high R-value.

4.6. Buckled configuration

Since PVDs deform together with the consolidation of soil, the discharge capacity of PVDs should be measured under deformed buckled conditions, which is the requirement in many ground-improvement and land-reclamation projects. However, the configuration of deformation or buckling is different from apparatus to apparatus and from test to test. Some types of discharge capacity tests are carried out with artificially deformed drains without soil, force kinking, folding and twisting, whereas others are carried out on PVDs which have been compressed together by the surrounding soil. Miura et al (1993) carried out discharge capacity tests on five different types of PVDs in a modified triaxial cell under five different configurations. Miura et al. (1993) reported that in the most extreme case of a PVD under a sharply bent condition, the discharge capacity decreased to 26% of the discharge capacity under the straight condition. A decrease in discharge capacity with an increasing strain was observed. Kamon et al. (1994) reported a reduction in discharge capacity of 35% to 70% when the axial strain reached 50%. Bergado et al. (1996) also reported that the discharge capacity of drains with sharp bends reduced to 10% to 20% of that of the straight condition (value). The twisting of the PVD also decreased the discharge capacity to 50% of that of the straight condition.

The discharge capacity of a particular type of drain (Type D) under various types of deformed or buckled configurations is shown in the Table 4. In the table, % is strain. “Shape folding” in two locations is termed as double folding. “Free bend” is just bending naturally to achieve the required strain; and therefore, it could be any shape. “Sharp bend” is when the drain is forced to bend sharply at a particular kink. It can be seen that both the free bend and the twisted condition causes a decrease in the discharge capacity by approximately 50% as compared to the straight condition, regardless of the strain or angle of twist. The folded condition was found to cause a significant decrease in the discharge capacity, by approximately 75% to 90%, as compared to a straight drain. Therefore, it is the most critical factor involved in the decrease in the discharge capacity of a PVD.

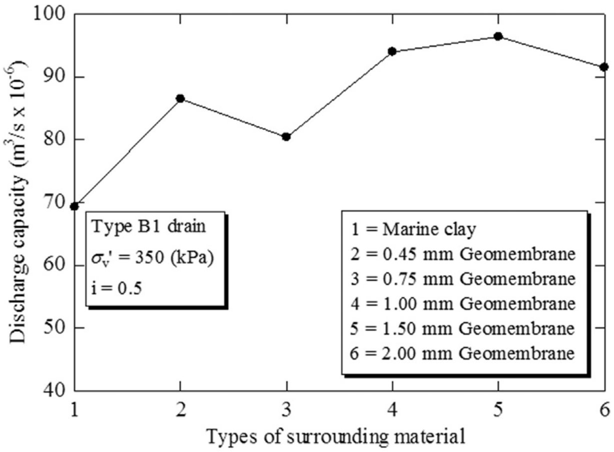

Fig. 12. Variation in discharge capacity due to variation in modulus of surrounding materials.

Table 4
Discharge capacity of Type D vertical drain under various deformation configurations (after Bergado et al., 1996).

Type of deformation	Discharge capacity ($m^3/s \times 10^{-6}$)
Non-deforming	62
15% Free bend	36
20% Free bend	32
90 Degree twisting	31
180 Degree twisting	30
20% Sharp folding	16
30% Sharp folding in 2 locations	5.5

For a particular type of surrounding clay under a hydraulic gradient, vertical pressure and test duration, the type of PVD controls the discharge capacity in a buckled configuration. In practice, the discharge capacity of a PVD at different buckled strain can be approximated from the straight drain, which is simply obtained from a conventional tester and the discharge capacity reduction factor. The discharge capacity reduction factor is widely varied and is dependent upon the PVD type and buckle configuration. The folded condition is the most significant factor and is suggested to be 0.75–0.90 for 20% and 30% strain based on the Bergado et al. (1996) results.

5. Conclusions

The discharge capacity is a critical parameter that controls the performance of prefabricated vertical drains (PVDs). The laboratory measurement of the discharge capacity required to obtain the optimal performance of PVDs by laboratory testing methods is still uncertain. The various factors that affect discharge capacity measurements have been reported in this paper.

Measurements of the PVD discharge capacity, without surrounding soil, were found to be affected by the dimensions of the apparatus. The 100 mm by 100 mm tester provided a more reasonable discharge capacity than the ASTM (2008) apparatus when PVDs were tested under the buckled condition. It was found that a tester with large dimensions is required especially for drains with a high discharge capacity because a tester with small dimensions results in the underestimation of the discharge capacity.

The discharge capacity of drains was found to decrease with an increasing hydraulic gradient and vertical pressure. The effect of the hydraulic gradient on the decrease in discharge capacity was remarkable at low levels of vertical pressure. The increase in vertical pressure decreased the thickness of the PVD, and hence, caused a decrease in the drainage channel and in the discharge capacity. Over time, the cross-sectional area of the PVD became smaller due to creep. The ingress of some fine materials into the drain and the clogging of the drainage channel became apparent. These phenomena caused a decrease in discharge capacity with time for a particular hydraulic gradient and vertical pressure. However, the creep effect on the decrease in discharge capacity became insignificant with tests of long durations.

For a particular vertical pressure on the soil surrounding the PVD, the discharge capacity was found to be controlled by the stiffness of the surrounding soil and the PVD. The large deformation of the soil surrounding the PVD, due to the low stiffness of the surrounding soil and the PVD, caused a decrease in the drainage channel. Finer soils resulted in the significant clogging of the PVD filter. The clogging of the filter and the reduction in the drainage channel led to a decrease in discharge capacity. The significant effect of the PVD deformation on the discharge capacity was evident by the results obtained with the kinked drain tester. Free bend, twisted and folded conditions decreased the discharge capacity as compared to a straight drain. All the test results showed that the deformation of PVDs under a folded condition is the most critical factor in reducing the discharge capacity.

The original contribution of this research was an evaluation of the factors that affect the current laboratory measurement techniques for the discharge capacity of PVDs. The current measurement techniques for the optimal performance of PVDs are still uncertain, despite research in this area by various researchers over the years. This research has evaluated the effects of various factors that could contribute to the present uncertainties, inclusive of the type of equipment, the hydraulic conductivity, applied stress, the surrounding material and the degree and type of deformation of the PVD, and recommends the critical factor that influences the discharge capacity.

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