Technical Paper by B.C. Rawes

CRITICAL PARAMETERS FOR SPECIFICATION OF PREFABRICATED VERTICAL DRAINS

ABSTRACT: This paper studies the properties of prefabricated vertical drains (PVDs) that are the controlling factors in the specification of PVDs. The ASTM D 4716 standard test method has generally become the most widely used test method for measuring the discharge capacity of a PVD. In this test method, the variation in clamping configurations and hydraulic gradient are not considered and can result in large differences in the discharge rate for the same PVD. After consideration of the relevant properties of a PVD, a suggested model specification is given.

KEYWORDS: Prefabricated vertical drain, Geotextile, Laminar flow, Hydraulic gradient, Permability, Pore size, Test method.

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1 INTRODUCTION

In the last 15 years, prefabricated vertical drains (PVDs) have almost completely replaced sand drains to accelerate the settlement of clay/silt soils under surcharge loading. The most important reasons for this change are listed below:

- The installation rate of PVDs is typically 5,000 linear metres per day, which results in a significantly lower project cost.
- There is no risk of PVDs breaking during installation, while sand drains may have discontinuities if the mandril is withdrawn too fast.
- There is no risk of shear failure of PVDs during settlement, while sand drains are vulnerable to shear failure during settlement.
- PVDs have high discharge capacities, typically 30×10^{-6} to 90×10^{-6} m^3/s, while a 0.35 m diameter sand drain has a discharge capacity of 20×10^{-6} m^3/s (Van Santvoort 1994).
- When installed with a properly designed mandril, smear effects are much less for PVDs than for large diameter sand drains. The zone of smear is directly proportional to the diameter of mandril used for installation.
- PVDs are factory produced materials and are quality controlled, whereas sand drains are subject to the quality variance of naturally occurring sands.

A generic PVD specification is urgently required in the industry. This is due in large part to the variable quality of the large number of PVDs available in today's market. Many engineers are aware of this problem but may not have an in-depth understanding of PVDs. Often, engineers over-specify in design, using parameters that are not relevant to the performance of a PVD, while at the same time not enough attention is given to the critical parameters. This type of design specification may limit the choice of a PVD to one or two types that may not be competitive or suitable for the project. In this paper, the important functions of PVDs are addressed. The paper concludes with a thorough design specification for the requirements of a high performance PVD.

2 PORE SIZE OF FILTER (GEOTEXTILE)

Prefabricated vertical drains are by design, nearly always used in silts or clayey silts with a D_{85} particle size of 15 to 30 μm. Therefore, it is necessary to have a fine pore size geotextile filter wrapping the core structure that will be compatible with the particle size distribution of the soil.

There are a large number of geotextile filter criteria put forward in various publications between 1975 and 1985. This work was reviewed and critiqued by Fisher et al. (1990) and Bergado (1992). Fisher and Bergado have proposed the following criterion for the maximum pore size of the PVD geotextile filter based on the apparent opening size (AOS):

$$AOS \leq 75 \ \mu m \qquad (1)$$

The ASTM D 4751 standard test method is a dry sieving technique that uses glass beads to determine the *AOS* of a geotextile. The test results in much larger O_{95} values for the same geotextile than wet sieving or hydrodynamic sieving techniques that also use glass beads (Bhatia et al. 1994). When wet sieving is employed, the O_{95} values can be as much as 50% smaller than the values obtained using ASTM D 4751. It should also be noted that ASTM D 4751 only measures down to a 75 μm particle size since below this size electrostatic forces between the glass beads would lead to an even greater variation between the results of wet and dry sieving test methods. However, the geotextile filter criteria are all empirical and are largely based on dry sieving techniques, hence the use of an *AOS* as a standard is acceptable to define the required O_{95} value for the PVD geotextile filter. An O_{95} value of 75 μm has been widely used over the last 15 years with good results, and in the light of the study by Bhatia et al. (1994), it can now be better understood why geotextile filters can retain silt particles in the size range of 15 to 30 μm.

3 PERMEABILITY OF THE FILTER

A widely used criterion for geotextile filter permeability is as follows:

$$k_{soil} \leq 10\,(k_{geotextile}) \tag{2}$$

where: k_{soil} = permeability of the soil; and $k_{geotextile}$ = permeability of the geotextile filter. This criterion is impractical for PVDs used in silt where the permeability of silts typically ranges between 10^{-7} and 10^{-10} m/s. Most geotextile filters have permeability values greater than 10^{-4} m/s; therefore, Equation 2 is not applicable to conditions where the permeability of the soil is orders of magnitude smaller than the geotextile permeability. Such a large difference between the soil and geotextile permeability values should not be considered as a built in factor of safety because of the risk of geotextile clogging. There has been very little study of clogging and the resulting reduction of permeability of geotextile filters used in silts. In addition, it should be noted that some manufacturers of PVDs, in an effort to reduce manufacturing costs, have moved to the use of lightweight calendered geotextile filters (the calendering process melts the geotextile fibres into small, approximately 1 to 2 mm, diameter circles over the entire surface of the geotextile) to meet the O_{95} specification. The direct result of calendering is to significantly reduce the permeability and reduce the O_{95} size of the geotextile instead of increasing strength.

4 DISCHARGE CAPACITY

Over the past 10 years, more than 250 million linear metres of PVDs have been installed. During this time of considerable increase in PVD use, many researchers have studied the pore water discharge capacity of PVDs.

One of the earliest studies conducted by Oostveen (1986) demonstrated, using actual site studies, that a maximum flow rate of 5×10^{-6} m^3/s existed in the PVDs investigated.

Koerner (1994) summarised in service PVD flow rate data; the maximum flow rates ranged between 1.5×10^{-6} and 5×10^{-6} m^3/s (50 to 150 m^3/year). These flow rates are based on actual site conditions, and thus, reductions in the discharge capacity of the PVDs caused by installation damage are incorporated in the flow rate values. Therefore, factors of safety are required when specifying a minimum discharge rate at a particular pressure. Particular consideration should be given to the effects of the following three main factors that cause a potential reduction of flow capacity:

- deformation and creep of the geotextile filter into the core profile;
- reduction of the permeability of the geotextile filter and deposition of fine particles in the core structure; and
- reduction of the flow capacity due to kinking and bending of the PVD during settlement.

Van Santvoort (1994) recommends that a PVD have a discharge capacity of 10×10^{-6} to 50×10^{-6} m^3/s at a confining pressure of 300 kN/m^2 if the PVDs in the field are greater than 10 m in length; and relative surface settlement is greater than 15% of the PVD length in less than 1.5 years. These required discharge capacities are in agreement with the information reported by Akagi (1994) (Figure 1). In Figure 1, the relationship between the minimum discharge capacity of the PVD, q_{wmin} , PVD length and permeability of the clay/silt are shown. The data in Figure 1 is based on data from major Far East

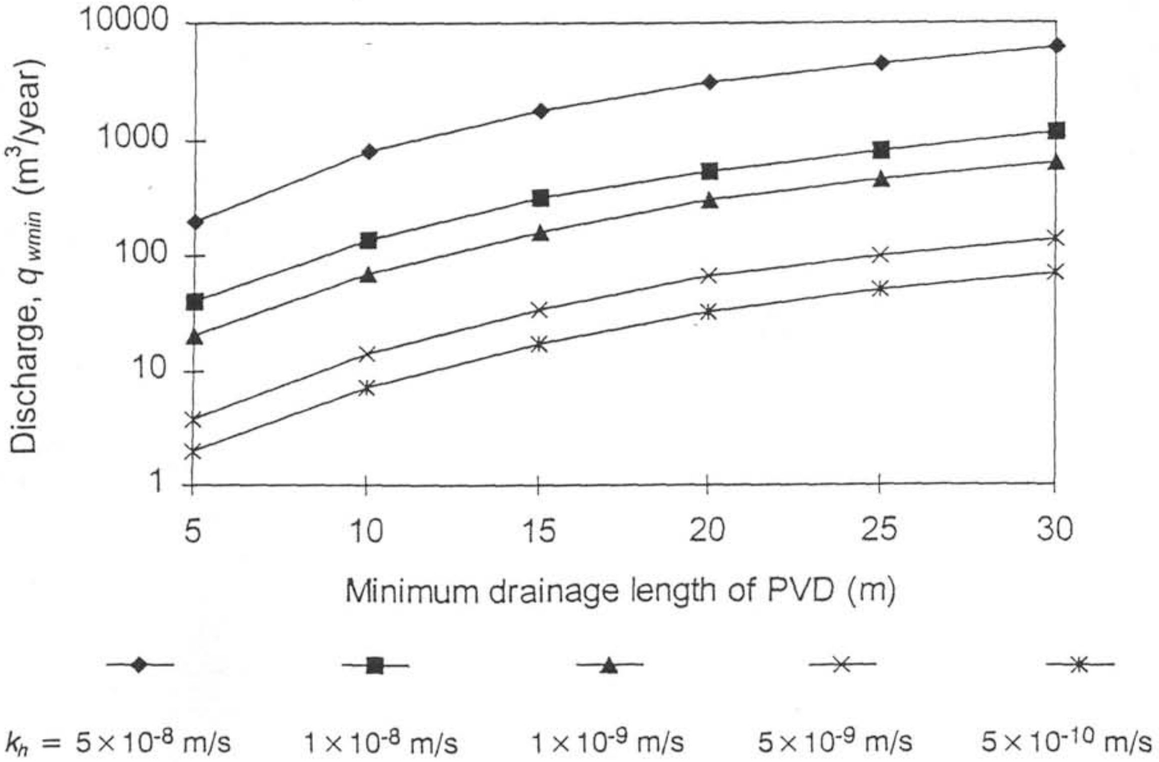

Figure 1. Minimum discharge capacity required for negligible flow resistance as a function of maximum drainage length of the PVD and horizontal permeability, k_h , of clay/silt soil (after Agaki 1994).

projects such as Changi Runway II, Chek Lap Kok and Changi-SIA Hanger in Singapore. In Figure 1, a q_{wmin} value of 1000 m^3/year (32×10^{-6} m^3/s) is obtained for a 30 m long PVD in a silt soil with a horizontal permeability, k_h , of 1×10^{-8} m/s.

Koerner (1994) studied the use of partial factors of safety (*FOS*) to account for the reduction of PVD discharge capacity in site-specific cases. From the results obtained, an overall average *FOS* value of 18.0 was recommended to be applied specifically to the results of the ASTM D 4716 standard test method for obtaining an ultimate flow rate. This *FOS* value of 18.0, results in a PVD having a flow rate of 90×10^{-6} m^3/s at a confining pressure of 300 kN/m^2 as measured using ASTM D 4716 with solid loading platens, and assuming a minimum required flow rate of 5×10^{-6} m^3/s in the field. The flow rate of 90×10^{-6} m^3/s is a much higher value than that reported by Van Sanvoort (1994) because of the different test methods. In Van Sanvoort's specification for required discharge capacity, it is assumed that the Delft test method is used, which allows for deformation and creep of the geotextile filter into the core structure. Thus, the required discharge rate specification is approximately half of the discharge rate using ASTM D 4716. The method used to establish the maximum flow rate of a PVD can give flow rate values at any given pressure that may vary by up to a factor of four. When testing a PVD for maximum flow capacity, the most important factors to consider are:

- The duration of loading (minutes, hours or days).
- The method of applying the load; solid steel clamps or foam rubber with a silt soil surcharge, or a neoprene sleeve and water pressure.
- The hydraulic gradient; when the hydraulic gradient, i, exceeds 0.1, laminar flow may not be present.

During the period 1975 to 1987, a working committee headed by Kremer and Oostveen made a detailed study of vertical drainage sponsored by the Technical University Delft, Public Works Department, The Netherlands, and the Road Construction Authority of The Netherlands. The results of this study have been a valuable source of formation to researchers. For example, a test method was proposed by Oostveen (1990) that replicates the in situ conditions for a PVD. A comparison was made between the compression of the PVD using clay/silt soil as a surcharge, and water pressure, with the PVD in a neoprene sleeve. The main disadvantage of using naturally occurring clay/silt is that the test results were not consistently repeatable and were difficult to perform. The use of a neoprene sleeve and water pressure for loading was found to be consistently repeatable and gave similar results to the clay/silt soil surcharge tests because the neoprene sleeve/water pressure assembly forced the filter into the core structure during the test. Figure 2 shows the schematic layout for the Delft PVD discharge test. The duration of the test is 28 days, during which the cell pressure is increased in steps of 50, 150, 250 and 350 kN/m^2 with each pressure held constant for 7 days. The value of q_w is determined at the beginning and end of each step.

The Delft test also attempts to replicate the field conditions where only small quantities of water are actually discharged from the drain. Hence, water flow through the PVD is controlled between 2.5×10^{-6} to 15×10^{-6} m^3/s and the head losses subsequently measured. From these readings and using Equation 3, a value of q_w for each cell pressure can be calculated and related to a design Q value of 5×10^{-6} m^3/s which is the expected maximum flow in the field. Hence:

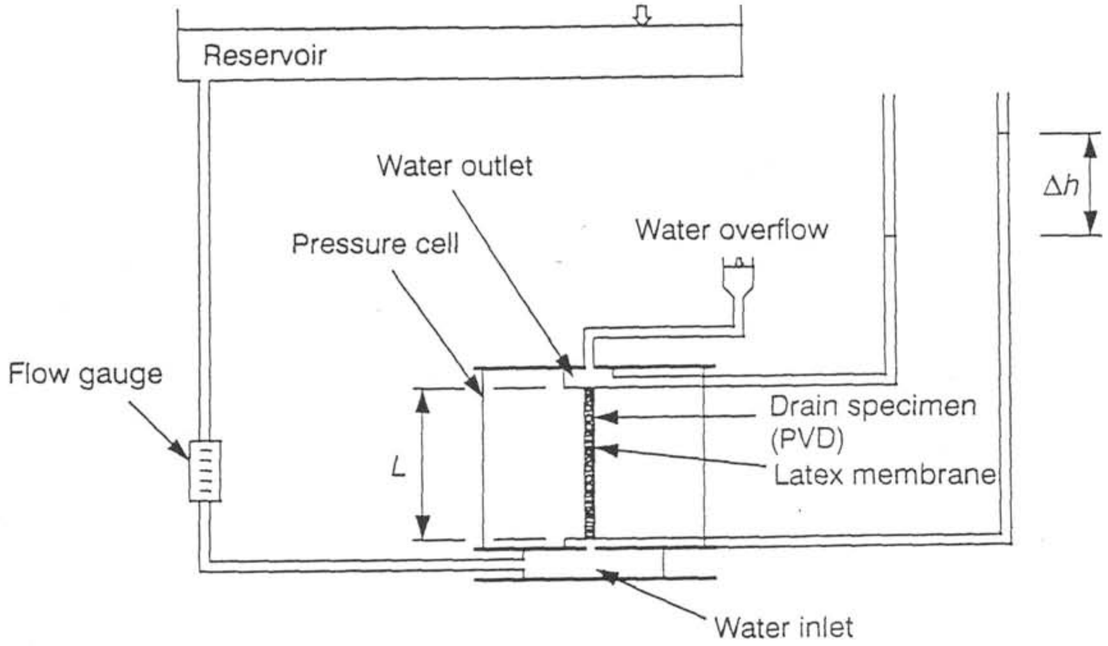

Figure 2. Schematic layout of Delft PVD discharge test apparatus.

$$q_w = \frac{Q}{i} \tag{3}$$

where: Q = water flow through the PVD; i = hydraulic gradient = $\Delta h/L$; and Δh = head loss over PVD length, L.

In Figure 3, the results from a Delft test apparatus are presented and compared with results from an ASTM D 4716 test, and the NTU (Nanyang Technological University) drain tester on the same PVD material. The value of q_w at a 350 kN/m^2 confining pressure varies between 35×10^{-6} and 79×10^{-6} m^3/s. The NTU and the ASTM D 4716 test methods are described below.

At the Nanyang Technological University of Singapore, a simple discharge capacity tester for PVDs (Broms 1994) was developed to provide a simple quality control test method for PVD projects in Singapore. In this test, the PVD is compressed, using site specific clay/silt material in contact with the PVD, in 100 kPa steps from 50 to 350 kPa. Each load step is held for one hour. The hydraulic gradient used as a reference for the results of the NTU test is $i = 0.5$, and the test is conducted to ensure laminar flow. Akagi (1994) noted the need to ensure laminar flow conditions and recommended a hydraulic gradient range for testing of $i = 0.2$ to 0.5.

Let us now consider the ASTM D 4716 discharge test which has been the most commonly specified standard discharge test in recent years. First, it should be understood that the ASTM D 4716 test was developed for geotextiles but not specifically for PVDs, unlike the Delft test which is a purpose designed test to simulate field conditions.

The most commonly used version of the ASTM D 4716 test (Figure 4) uses steel base and top platens covered with a thin rubber layer of low compressibility. This prevents any significant deformation of the geotextile filter into the core structure of the PVD which is the greatest cause of reduction in the discharge capacity of an in situ PVD.

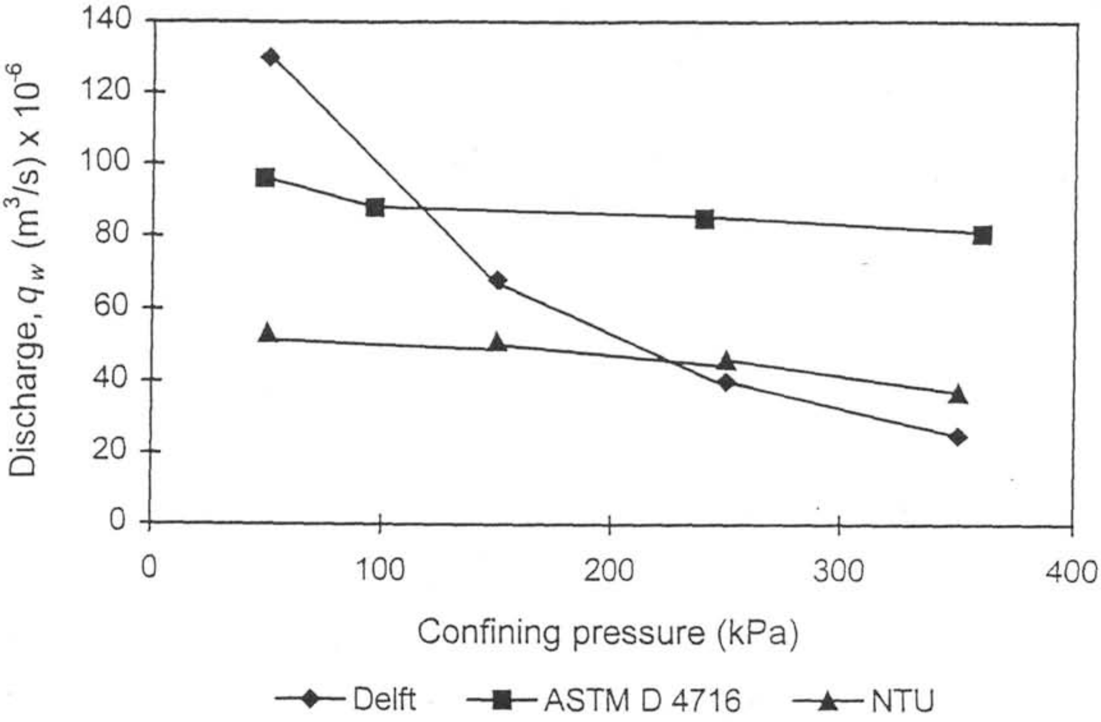

Figure 3. Comparison of q_w values for the same PVD using different test methods.

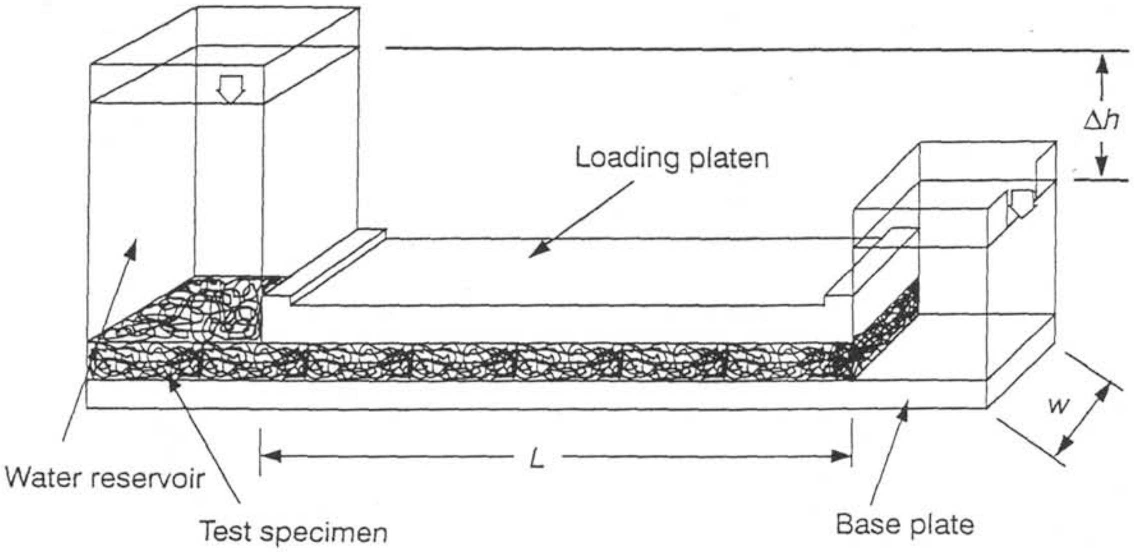

Figure 4. Schematic layout of ASTM D 4716 test apparatus.

There is an option to use closed-cell foam rubber layers on one or both steel platens which would allow some movement of the geotextile filter into the core structure. However, neither the thickness nor the type of closed-cell foam rubber is specified in the ASTM D 4716 test and variations in these parameters can lead to different results between laboratories. The time for each load increment in the ASTM D 4716 test is specified as a minimum of 15 minutes to allow for uniform flow conditions to be established. This relatively short time period does not allow long term creep of the geotextile filter into the PVD core structure to develop. Long term creep of the PVD specimen is observed in the Delft test when load increments are held constant for 7 days. However, there is no reason not to extend the loading time period for ASTM D 4716 tests to account for long term creep.

The hydraulic gradient is varied in the ASTM D 4716 test rather than the volume of water flow through the PVD, as in the Delft test. Unfortunately, this results in many testing institutions and laboratories using large hydraulic gradients, typically between i = 0.5 to 1.5 and some up to $i = 10$, in order to obtain easily measured large flow rate volumes. However, the flow rates generated by these hydraulic gradients are far in excess of the actual field conditions and, more importantly, frequently cause "turbulent rather than laminar flow conditions" in the PVD. Thus, the results obtained are invalid since Darcy's law does not apply in turbulent flow conditions, and the q_w values obtained from Equation 3 are incorrect. Also, the theory of radial flow to vertical drains becomes invalid in turbulent flow conditions. The hydraulic gradient range which should be used for testing PVDs according to the ASTM D 4716 test is $i = 0.05$ to 0.3. This is substantiated by Clause 8.3, *Gradient Selection*, in the ASTM D 4716 test, where a "maximum" hydraulic gradient of 0.1 is suggested for tests intended to model pressure flow conditions. "Pressure flow" is defined as " ... flow in a direction parallel to the plane of a geotextile or related product driven predominantly by a differential fluid pressure.". Note 3 of the ASTM D 4716 test also states that the test must be conducted under laminar flow conditions. Therefore, it can be concluded that unless laminar flow is present the testing is not in accordance with ASTM D 4716. When laminar flow conditions are present, the plot of discharge versus hydraulic gradient is a straight line and the value of q_w remains constant. This can be seen in Figure 5 where the discharge from two types of PVDs measured using the ASTM D 4716 test have been plotted against the hydraulic gradient. The PVD specimen, with an extruded polymeric sheet formed with a castellated core cross section, shows a straight line plot indicating laminar flow. However, the PVD specimen with a filament core (extruded core of polymeric filaments in a three-dimensional structure) clearly shows a non-linear plot indicating that turbulent flow is present. With only three measured points, it cannot be ascertained where the change to turbulent flow occurs, thus additional testing was performed using hydraulic gradient values of 0.01 to 1.0. These results are shown in Figure 6.

From Figure 6 it can be seen that the change from laminar to turbulent flow occurred between $i = 0.2$ to 0.3. Using the data from Figure 6, the following q_w values are calculated using Equation 3 for $i = 0.1$ and 1.0:

$$q_w = \frac{5.79 \times 10^{-6}}{0.10} = 57.9 \ \text{m}^3/\text{s} \times 10^{-6} \qquad \text{at } i = 0.1 \tag{4}$$

$$q_w = \frac{30.7 \times 10^{-6}}{1.0} = 30.7 \ \text{m}^3/\text{s} \times 10^{-6} \qquad \text{at } i = 1.0 \tag{5}$$

Therefore, when PVD discharge capacities are compared at $i = 1.0$, an unrealistic value for q_w is obtained using the ASTM method of test. The value of q_w calculated in Equation 5 using $i = 1.0$ is almost half the value of q_w calculated using Equation 4 and $i = 0.1$.

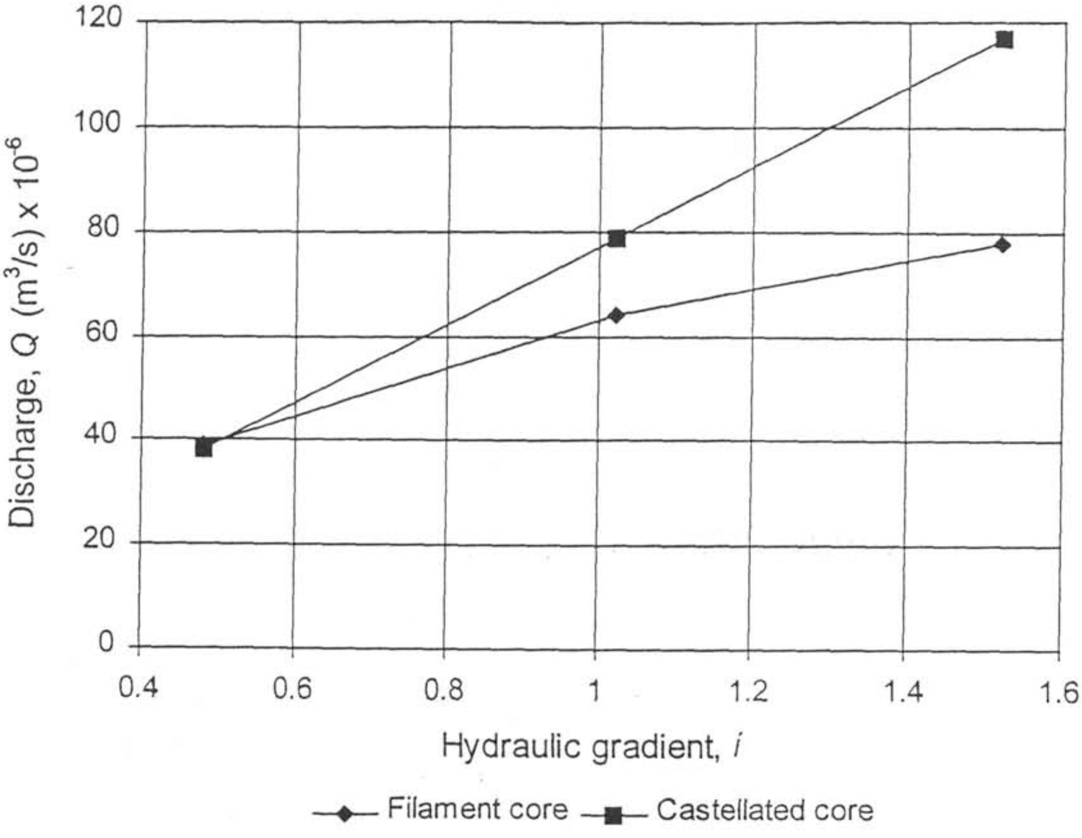

Figure 5. Discharge versus hydraulic gradient for two PVDs at 360 kPa confining pressure.

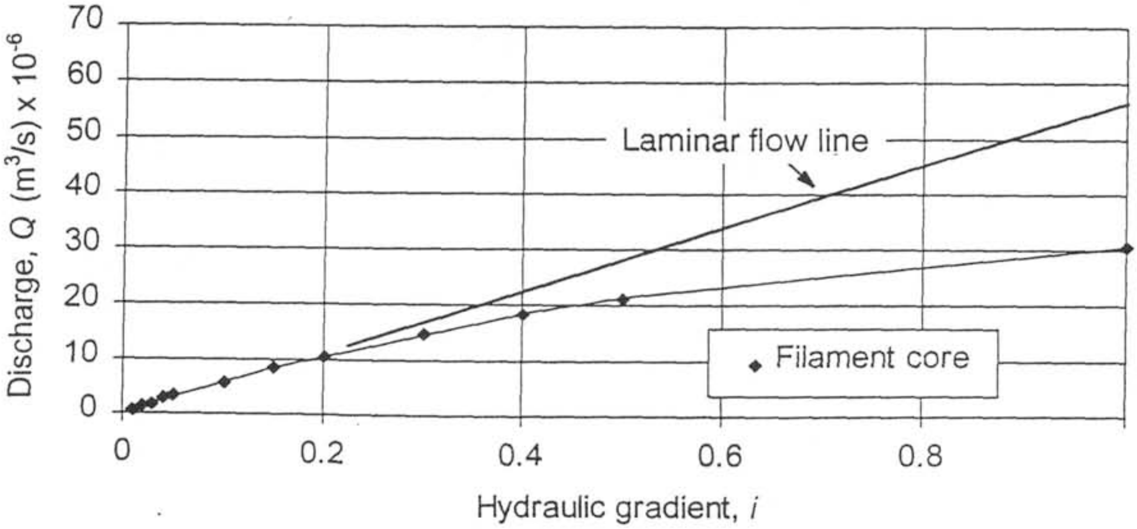

Figure 6. Discharge versus hydraulic gradient at 360 kPa confining pressure for a filament core PVD.

5 TENSILE STRENGTH

The tensile strength of a PVD has no direct effect on its performance with respect to accelerating the consolidation of soft clay/silt soils.

The tensile strength of PVDs is a factor related to the installation equipment used by the installer, and should be greater than 0.5 kN at a strain greater than 2%, but less than 10% (Van Santvoort 1994). Tensile strength of PVDs at strains greater than 10% are of little use since the typical castellated core profile becomes so distorted at strains greater than 10% that its function is significantly compromised. Therefore, it is more important that the installation rig is suitable for the installation of a site specific PVD. A properly maintained installation rig, with smooth operating guide rollers to feed the PVD to the top of the rig and down into the mandril, will impart a tensile load of less than 0.5 kN on the PVD.

The ASTM D 4595 and ASTM D 4632 test methods are commonly used to determine the tensile characteristics of PVDs. The ASTM D 4632 standard test is a grab tensile test using clamps 25 mm wide by 51 mm long. The ASTM D 4595 standard test method uses 200 mm wide clamps that allow the full width of the PVD to be tested. It should be noted that this is a modification of the ASTM D 4595 test procedure since the PVD width is usually only 100 mm. The strength result should be expressed as the total load per unit width of the PVD. The grab tensile test will typically give lower strength results, at higher strain values, because of the clamping configuration and is not representative of the way in which the load is applied to a PVD during installation. The ASTM D 4595 test is therefore the preferred test method because it more accurately replicates the way tensile load is applied to the PVD when the material passes over the full width rollers of an installation rig.

6 PHYSICAL PROPERTIES

The polymers most frequently used for manufacturing PVDs are polyester, polyamide, polypropylene and polyethylene. There are no advantages or disadvantages in using one polymer over the other, and a specification should not preclude or favour any one or combination of polymers.

Prefabricated vertical drain widths of 0.3 m have been used on occasion, but because the standard installation equipment is designed for 0.1 m wide PVDs, most projects are designed and specified for 0.1 m wide PVDs. The thickness of PVDs typically varies between 3 to 5 mm, but this is an irrelevant PVD characteristic because the compressibility of the core and deformation of the geotextile filter into the core structure are the controlling factors for PVD discharge capacity. Note that the discharge capacity is the most significant property of PVDs.

The theory of radial consolidation assumes that the liquid drains into a circular drain. The equivalent diameter of a PVD, which is used in drainage calculations, is defined as the equivalent drain diameter and is typically expressed as:

$$d_e = \frac{a + b}{2} \tag{6}$$

where: a = width of the PVD = 100 mm (typical); b = thickness of the PVD = 3 to 5 mm; and d_e = equivalent diameter of PVD. For a 4 mm thick PVD, the following typical value of d_e results:

$$d_e = \frac{100 + 4}{2} = 52 \text{ mm} \tag{7}$$

As can be seen from Equations 6 and 7, all 100 mm wide PVDs will have essentially the same equivalent diameter of 52 mm, since the variation of PVD thickness is only 1 or 2 mm.

7 ON SITE QUALITY CONTROL

Any manufactured material should undergo quality control testing with respect to a design specification. This testing can consist of a full set of tests at the beginning of the contract, to establish compliance with the specification, followed by quality control tests such as tensile strength and mass per unit area to ensure product consistency. Such a quality control program would be completely satisfactory when the PVD is manufactured in accordance with ISO 9001 or ISO 9002 standards.

A PVD that is not manufactured under an international quality control standard should be tested for full compliance with the specification every two million linear metres of installed product, or every two months if the installation rate is greater than one million meters per month.

8 MODEL SPECIFICATION

A design specification should be generic, and the required design requirements should reflect the actual engineering needs for the material to perform properly and should not be modelled on a particular manufacturer's specification. Using the information presented in this paper, and addressing the major factors and requirements of a PVD, a model design specification is proposed in Table 1.

Table 1. A model prefabricated vertical drain design specification.

Property	Units	Requirement	Standard test method
Pore size of geotextile, O_{95}	μm	≤ 75	ASTM D 4751
Permeability of geotextile, $k_{geotextile}$	m/s	$\geq 1 \times 10^{-4}$	ASTM D 4491
Discharge capacity, q_w , under laminar flow conditions and at a confining pressure of 350 kN/m^2	m^3/s	$\geq 50 \times 10^{-6}$	ASTM D 4716 (6 mm closed-cell foam rubber boundary layer)
Tensile strength of PVD at $\leq 10\%$ strain	kN	1.0	ASTM D 4595
Width of PVD, a	mm	$95 < a < 105$	–

Note: Nonwoven geotextile filter and core structure should be manufactured from a polymer material which will have a life expectancy of more than 3 years in naturally occurring clay/silt soils.

Standard ASTM methods of test are chosen for quality control testing since they are the most widely used testing standards in the Far East where most PVDs are used. The standard ASTM D 4716 test is not, however, the best test method for a PVD. Unlike the Delft test and the NTU test, the ASTM D 4716 test is a standard code of practice, and therefore, testing laboratories will be more familiar with it. A specification requirement to use 6 mm thick closed-cell foam rubber between the clamps and the PVD in the the ASTM D 4716 test to better model the site situation is included in the model specification even though there is likely to be a variation between laboratories in the type of rubber used. For PVDs where the geotextile filter is not fixed to the core structure and loose geotextile filter material can easily be pushed into the core, unrealistically high discharge capacity results will be measured when steel platens are used without the foam rubber.

9 SUMMARY

The model PVD specification has been prepared in an effort to ensure that the engineer receives a quality PVD that should be acceptable while not eliminating the element of competition between suppliers.

The PVD has two main components, a geotextile filter and a core structure. Only the geotextile is tested as a separate component (pore size and permeability), all other specified properties are for the complete PVD. The values presented in the model specification for geotextile pore size and permeability are easily achieved by all geotextile manufacturers and match current geotextile filter criteria. In particular, the maximum pore size of 75 μm has been proven in practice to be effective. Since the wet sieving technique gives O_{95} values 50% less than those obtained using a dry sieving technique (Bhatia et al. 1994), then the choice of a maximum geotextile pore size value of 75 μm is further reinforced.

In carrying out a project, much attention is often paid to the material tensile strength. This may be due to the ease with which this test can be performed for comparison purposes, and in part due to manufacturers of higher strength PVDs who strongly promote the high tensile strength of their PVDs. As has been discussed, the tensile strength required for installation of a PVD is only 0.5 kN. When installing PVDs using installation rigs that are not of the highest standard (i.e. significant roller friction, and therefore, an increase in load on the PVD), a tensile strength specification of 1.0 kN will allow for the load increase in the PVD. It is considered important, in order to simulate site conditions as closely as possible, that the ASTM D 4595 wide-width strip test, modified to suit the actual width of the PVD and reported as the total load, is used to measure the tensile strength of PVDs. The ultimate strength of a PVD, which occurs beyond 10% strain, should not be considered in a PVD comparison since this is outside the maximum discharge performance of the PVD due to core distortion.

The discharge capacity, q_w, is one of the most important characteristics of a PVD, but unfortunately, it is the most difficult test to perform, and different laboratories may obtain varying results for the same PVD. It is believed that by using the ASTM D 4716 standard test method together with closed-cell foam rubber between the clamps and the PVD, and careful attention paid to ensure laminar flow, that better agreement between laboratories could be achieved. It should be noted that a hydraulic gradient value is not specified in the ASTM D 4716 test. This test method specifies only that laminar flow should be present. The comparison and specification of PVDs is usually based on the q_w value from which Equation 3 gives the theoretical discharge capacity at $i = 1.0$. In field conditions, the hydraulic gradient at which PVDs operate is typically less than 0.1, and in fact this hydraulic gradient value reduces with time. However, comparisons of PVDs on the basis of q_w values has been the standard within the industry for more than 15 years and has always been the basis of comparison. It would require a major re-education of design engineers to change this process, and it would be changed for no useful advantage.

In conclusion, it is hoped that the author has brought to the attention of engineers the most important properties of PVDs that control the proper function of a PVD, and that should form the basis of a specification, rather than properties such as PVD mass per unit area and thickness. The PVD mass per unit area and thickness should only be used for quality control after selecting a specific PVD for a project.

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NOTATIONS

Basic SI units are given in parentheses.

a = width of PVD (m)
AOS = apparent opening size of geotextile (m)
b = thickness of PVD (m)
D_{85} = particle size such that 85% of the particles by weight are smaller than that size (m)
d_e = equivalent diameter of PVD (m)
FOS = factor of safety (dimensionless)
i = hydraulic gradient (dimensionless)
$k_{geotextile}$ = permeability of geotextile (m/s)
k_h = horizontal permeability of soil (m/s)
k_{soil} = permeability of soil (m/s)
L = length of PVD (m)
O_{95} = geotextile opening size such that 95% of pores are smaller than that size (m)
Q = flow rate in PVD (m^3/s)
q_w = discharge capacity (m^3/s)
q_{wmin} = minimum discharge capacity (m^3/s)
w = width of test specimen in ASTM D 4716 method of test (m)
Δh = hydraulic head loss (m)