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THE BEHAVIOR OF FLOW CONDITION IN PREFABRICATED VERTICAL DRAINS DUE TO INCREMENTAL CONFINING PRESSURE

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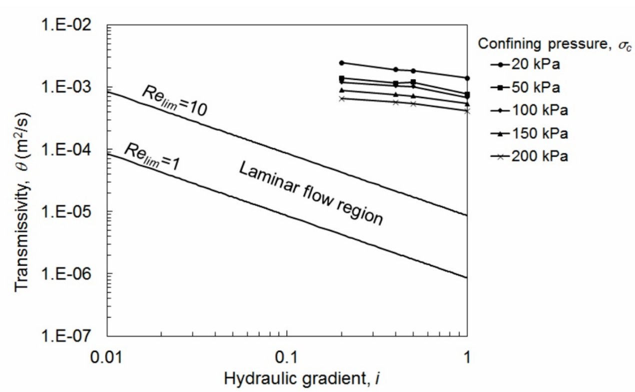
Graphical abstract



Abstract

Prefabricated Vertical Drains (PVDs) are commonly used in geotechnical engineering to speed the consolidation of soft and compressible soils. Understanding the behavior of PVDs under various load conditions is essential for their efficient design and implementation. This research aims to improve the performance and efficacy of PVD systems in geotechnical engineering applications by investigating and comprehending the behavior of flow conditions in PVDs under incremental confining pressure. Three PVD samples varying in thicknesses have been evaluated in the laboratory to determine their discharge capacity and transmissivity under various hydraulic gradients. The PVD was subjected to incremental confining pressures between 50 and 200 kPa. The apparatus utilized in this study was designed by following ASTM D4716. The flow condition was determined by limiting the hydraulic gradients and calculating the turbulence degree of the flow. The analysis results showed that the flow inside PVD is non-laminar, and the PVD with the larger cross-section is more resilient to deviations in the hydraulic gradient. The proposed equations accurately predicted the discharge capacity of PVDs under increasing confinement pressures, and a comparison with experimental results revealed a high level of concordance. Particularly for PVDs with larger cross-sectional areas, the hydraulic gradient significantly affected the discharge capacity.

Keywords: Laminar, Turbulent, Discharge capacity, Geosynthetics, Soil improvement.

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1.0 INTRODUCTION

Prefabricated vertical drains (PVDs) are commonly used in geotechnical engineering to speed the consolidation of soft and compressible soils [1]–[6]. These drains are formed of highly permeable synthetic or natural materials that are positioned vertically and offer effective channels for water to drain from the soil. By improving the drainage capacity, PVDs help to minimize the consolidation time, strengthen the soil stability, and prevent problems like settlement and liquefaction.

Discharge capacity (q_w) is the most vital property of vertical drainage design, which controls the performance of Prefabricated Vertical Drains (PVD) as a drainage [7]–[9]. The effectiveness of PVD depends on the decent observation of its hydraulic performance. Thus, inaccurate discharge capacity value data can lead to an improper consolidation rate prediction [10]. PVD should have an acceptable discharge capacity value to operate effectively [11], with the recommended value of the required discharge capacity being greater than 3.2×10^{-6} to 4.8×10^{-6} m^3/s [12].

The discharge capacity value decreases when the PVD is subjected to confining pressure, mainly because of the thickness reduction [13]. The thickness of PVD is critical in discharge capacity determination since it is related to the drainage channel area [14]. Research conducted by [15] stated that the criteria that influence the discharge capacity of drains are the stress period and the stress magnitude applied to the drains, the structural and physical characteristics, and the soil boundary's characteristics.

The most popular approach to measure the geosynthetics' flow capacity is the hydraulic transmissivity test standard provided by [16], a procedure to observe the influence of confining pressure on the transmissivity of PVD with a constant head flow mechanism. Research about the discharge capacity of PVD has been widely conducted using laboratory measurements, either employing an ASTM device or a modified triaxial device, with and without soil confining [17]–[20].

Understanding the behavior of PVDs under various load conditions is essential for their efficient design and implementation. Therefore, many researchers studied the effect of incremental confining pressure on the flow condition within the PVDs [18], [19], [21]. Confining pressure refers to the tension exerted on the soil surrounding the PVDs, which can vary depending on variables such as the depth of the drain, soil properties, and the magnitude of external loads.

This study considers the behavior of hydraulic parameters of PVD under incremental confining pressures, including the determination of flow conditions in PVD and the degree of turbulence value. This paper also discusses the relation between discharge capacity and confining pressure to establish an equation to predict the value of discharge capacity under certain confining pressure. This research aims to improve the performance and efficacy of PVD systems in geotechnical engineering applications by investigating and comprehending the behavior of flow conditions in PVDs under incremental confining pressure. This knowledge can contribute to the development of more precise design guidelines while improving the overall effectiveness of ground improvement techniques.

2.0 FLOW CONDITION IN PVD

Using numerical calculations, [22] observed that in most drainage systems, the fluid flow in the sand and needle-punched non-woven geotextiles is typically smooth and orderly (laminar). In the case of gravel and geosynthetics with a biplanar section, however, the flow is generally disorderly and unpredictable (non-laminar) unless there is minimal or no geotextile intrusion into the PVD channels.

Flow is considered laminar if the Reynolds number value, *Re*, is equal to or below Re_{lim}, with the limit value of Re_{lim} being between 1 to 10 for geonets [23]. The laminar flow condition for biplanar geosynthetics also can be determined by limiting its hydraulic gradient (i_{lim}), employing Eq. (1) or (2) depending on the available parameter.

$$i_{\lim} = \left(\frac{\eta}{\rho}\right)\left(\frac{5-4n}{2}\right)\frac{Re_{\lim}}{\theta} \tag{1}$$

or,

$$i_{\lim} = \frac{2Re_{\lim}}{\beta_k g}\left(\frac{\eta}{\rho}\right)^2\left(\frac{5-4n}{n}\right)^3\left(\frac{1}{t_D}\right)^3 \tag{2}$$

where η is the value of water viscosity (kg/ms), ρ is the value of water density (kg/m^3), β_k is the factor of tortuosity (with the suggested value of 0.1 for porous media), g is the gravity acceleration, and t_D is the thickness of geosynthetics.
Substituting the value of porosity, *n*, which was obtained from Eq. (3), which was proposed by [24] to Eq. (2), the limiting hydraulic gradient is given in Eq. (4):

$$n = 1 - \frac{\mu}{\rho_P t} \tag{3}$$

$$i_{\lim} = \frac{2Re_{\lim}}{\beta_k g}\left(\frac{\eta}{\rho}\right)^2\left(\frac{1+\frac{4\mu}{\rho_P t_D}}{1-\frac{\mu}{\rho_P t_D}}\right)^3\left(\frac{1}{t_D}\right)^3 \tag{4}$$

where μ is mass per unit area (kg/m^2), and ρ_P is polymer density (kg/m^3).

The flow can be laminar or turbulent as a fluid flows through a porous material, such as granular or geosynthetic materials. However, a range of flow behavior between these two extremes is known as semi-turbulent flow. This flow is neither entirely laminar nor completely turbulent. For semi-turbulent flow in a porous medium, the apparent flow velocity is expected to be proportional to the hydraulic gradient. Despite this, the relationship between flow velocity and hydraulic gradient lies between the powers of 0.5 and 1 for turbulent flow and laminar flow, respectively [25].

[23] also stated that the limited hydraulic gradient values for geosynthetics with the approximate porosity value of 0.8 are between 0.0001 to 0.1, which is particularly small. For this reason, it can be concluded that the flow inside geosynthetics is mainly non-laminar.

3.0 FLOW TURBULENCE DEGREE IN PVD

The flow condition in geosynthetics can be characterized as turbulent or laminar using the turbulence degree, *m*. A flow is considered semi-turbulent when the *m* value is between 0.5 and 1.0. While if the m value is [0.5, the water flow is defined as turbulent, and when the m value is ≥1, the water flow is defined as laminar. The determination of *m* when the transmissivity data are known may be measured by applying Eq. (5), which is proposed by [25].

$$m = 1 + \frac{\log\theta_1 - \log\theta_2}{\log i_1 - \log i_2} \tag{5}$$

where *m* is the flow turbulence degree for the flow with hydraulic gradients ranging from i_1 to i_2, θ_1 is the transmissivity of PVD at i_1, and θ_2 is the transmissivity of PVD at i_2.

4.0 RELATIONSHIP OF HYDRAULIC CONDUCTIVITY AND DISCHARGE CAPACITY

Darcy's law states that the apparent velocity (v_{app}) is the ratio of liquid discharge per unit area of a porous medium, which is shown in Eq. (6). [26] stated that in non-laminar flow, the hydraulic conductivity depends on the hydraulic gradient or apparent hydraulic conductivity, which is symbolized as $k_{(i)}$.

$$v_{app} = \frac{Q}{A} = k_{(i)} i \tag{6}$$

where Q is the water discharge per unit time (m3/s), and A is the drainage channel area. Thus, the apparent hydraulic conductivity can be written as Eq. (7).

$$k_{(i)} = \frac{v_{app}}{i} \tag{7}$$

For a drainage channel with consistent thickness, the value of apparent transmissivity ($\upsilon_{(i)}$) can be determined as a function of apparent hydraulic conductivity and drainage layer thickness, as shown in Eq. (8).

$$\theta_{(i)} = k_{(i)} t_D \tag{8}$$

Transmissivity is defined as the discharge capacity of geosynthetics per unit width. Therefore, the discharge capacity of geosynthetics can be expressed in Eq. (9).

$$\frac{q_w}{w} = k_{(i)} t_D \tag{9}$$

Hence yields Eq. (10),

$$q_w = k_{(i)} t_D w = k_{(i)} A \tag{10}$$

5.0 RESEARCH METHODS

5.1. Materials

Three types of PVD with a width (w) of 100 mm and a thickness (t) of 3, 4, and 5 mm were used in this study, i.e., PVD-T3, PVD-T4, and PVD-T5, respectively. The entire specimens have a non-woven and heat-bonded filter with a harmonica core shape. The properties of PVD specimens are shown in Table 1.

5.2. Apparatus

The apparatus used in this study was developed by [14] to observe the discharge capacity of the PVD-PHD connection system. It was designed by adopting ASTM D4716 to simulate the in-situ conditions where the PVDs are confined by lateral earth pressure and the PHDs are confined by soil preloading. The apparatus had two particular components: the cylinder compression chamber made from 10 mm thick acrylic with a diameter of 200 mm and a height of 500 mm, and the box compression chamber with 470 × 460 × 700 mm dimensions. A constant pressure device was used to control the pressure mechanism inside the cylinder compression chamber, similar to the instrument on a triaxial soil test. The box compression chamber was only used as an outflow tank considering this study only observed the discharge capacity of PVD. The schematic layout of the apparatus is shown in Figure 1.

5.3. Test Procedure

The purpose of the test is to examine the flow condition within the prefabricated vertical drain (PVD) under varying hydraulic gradients, excluding the effects of soil confinement and clogging.

For testing, a 500-millimeter-long specimen wrapped in latex is specified. The sample is positioned within the compression chamber of a cylinder.

In stages, increasing confining pressures are applied to the specimen. The range of confining pressures is from 50 to 200 kPa, with each loading stage increasing by 50 kPa. At the initial loading, a 20 kPa confining pressure was implemented to observe the water flow at the initial time, assuming that the initial loading does not affect the PVD thickness. Previous research conducted by [10] advised the selection of confining pressure values, which confirmed the significant impact of lateral earth pressure exceeding 150 kPa on PVD discharge capacity.

The experimental settings utilized a mechanism with a constant head flow. This required adjusting the elevation of the inlet reservoir in order to modify the hydraulic gradient (i) value. This adjustment was intended to maintain hydraulic gradients in laboratory measurements that closely approximate in-situ conditions [10]. The recommended hydraulic gradient typically ranges from 0.1 to 0.3 [19]. However, based on previous research [7], a hydraulic gradient 0.5 was considered more suitable for laboratory measurements of discharge capacity.

The hydraulic gradients applied in this study were thoroughly selected to convey a range of values adequately. In particular, gradients of 0.2, 0.4, 0.5, and 1 were selected. These values were determined by dividing the head difference by the PVD specimen's length. The purpose of this study was to assess the effect of varying flow conditions on the performance of the PVD system by taking into account varied hydraulic gradients.

The average water discharge was measured to evaluate the performance of the PVD system under varying hydraulic gradients. This measurement was performed following a 15-minute period of seating for each loading stage. By allowing sufficient time for settling, the study intended to obtain accurate and representative data on the flow conditions within the PVD.

Table 1 Properties of PVD specimens (modified from [14])

	Properties	PVD-T3	PVD-T4	PVD-T5
Dimensions	Thickness, t (mm)	3	4	5
	Width, w (mm)	100	100	100
Filter	Thickness (mm)	0.24-0.25	0.24-0.25	0.24-0.25
	Material	PET	PET	PET
	AOS (μm)	75-90	75-90	75-90
	Permeability (mm/s)	0.347	0.358	0.3
Core	Material	PP	PP	PP
	Elongation at break (%)	46	45	43
	Tensile strength (kN/m)	2.53	2.55	2.7
Composite	Mass per unit area, μ (kg/m^2)	0.48	0.52	0.62
	Polymer density, ρ_P (kg/m^3)	898.54	898.54	898.54
	Unit weight (gr/m)	70	75	80
	Initial porosity (n)	0.822	0.855	0.862

Note: PET = Polyethylene terephthalate
PP = Polypropylene

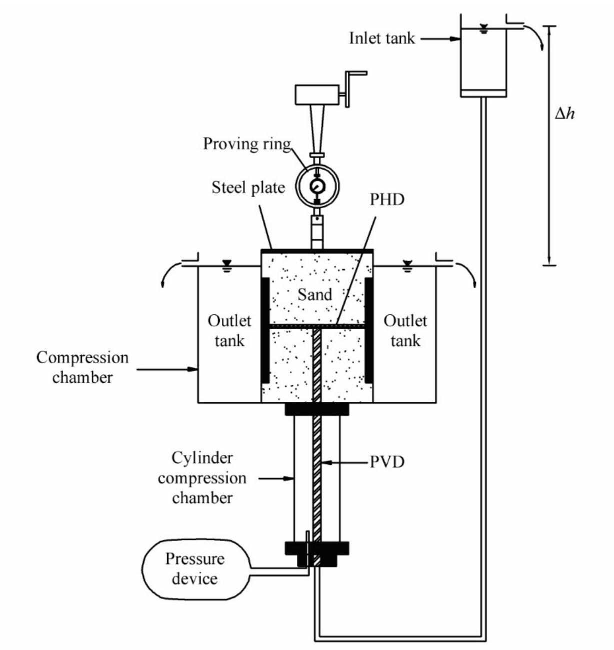

Figure 1 Schematic layout of the apparatus (modified from [27])

6.0 RESULTS AND DISCUSSION

6.1. Interpretation Of Flow Condition For Pvd

A limiting hydraulic gradient method was used to determine the PVD's flow condition by employing Eq. (1) under these assumptions: PVD core was considered as a biplanar geonet, the value of water density is 1000 kg/m^3, the value of water viscosity is 0.001 kg/ms at 20^{o}C, and the values of porosity were taken from Table 1. The expressions to define the value of i_{lim} for PVD-T3, PVD-T4, and PVD-T5 are shown in Eqs. (11) to (13), respectively.

$$i_{\lim} = 6.8\times10^{-7}\frac{Re_{\lim}}{\theta}\text{, for PVD-T3} \quad (11)$$

$$i_{\lim} = 6.5\times10^{-7}\frac{Re_{\lim}}{\theta}\text{, for PVD-T4} \quad (12)$$

$$i_{\lim} = 6.38\times10^{-7}\frac{Re_{\lim}}{\theta}\text{, for PVD-T5} \quad (13)$$

The transmissivity, denoted by θ, was determined at the limit condition using Equations (14) to (16) with $i_{\lim}$ values ranging from 0.01 and 1.0 and $Re_{\lim}$ values between 1 and 10. These calculations provided for plotting transmissivity values as boundary conditions for laminar flow in PVD-T3, PVD-T4, and PVD-T5, as shown in Figures 2, 3, and 4, respectively. In accordance with the recommendation [26], a logarithmic scale was implemented to improve the visualization of hydraulic parameters.

The position of the plotted curves relative to the laminar flow region was examined to evaluate the flow condition within the geosynthetic. If a curve fell within this region, laminar flow would be indicated. In order to assess the flow condition of the PVD specimens, the graphs included transmissivity values obtained from research conducted by [28].

$$\theta = 6.8\times10^{-7}\frac{Re_{\lim}}{i_{\lim}}\text{, for PVD-T3} \quad (14)$$

$$\theta = 6.5\times10^{-7}\frac{Re_{\lim}}{i_{\lim}}\text{, for PVD-T4} \quad (15)$$

$$\theta = 6.38\times10^{-7}\frac{Re_{\lim}}{i_{\lim}}\text{, for PVD-T5} \quad (16)$$

Figures 2-4 indicate that all specimen curves are located on the upper-right side of the upper laminar boundary curve (Re = 10) or outside the laminar boundary region. This observation indicates that the flow within the PVD specimens was not laminar.

The position of the PVD specimens outside the laminar flow region on the graphs suggests that the flow conditions within the PVD specimens did not meet the criteria for laminar flow. The finding is agreeable with the statement proposed by [26]. This insight emphasizes the importance of contemplating non-laminar flow behavior when analyzing and designing PVD systems.

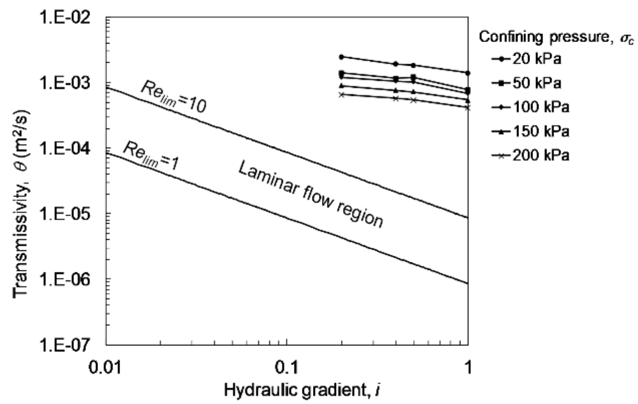

Figure 2 Laminar flow boundary for PVD-T3.

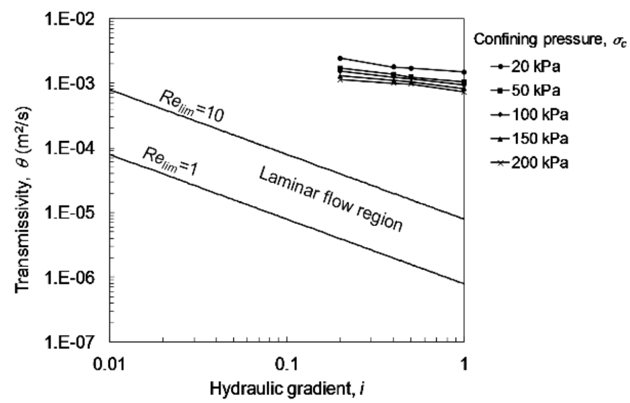

Figure 3 Laminar flow boundary for PVD-T4.

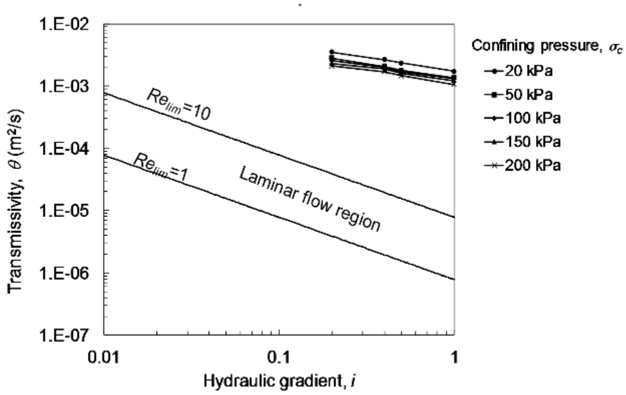

Figure 4 Laminar flow boundary for PVD-T5

6.2. Determination Of Turbulence Degree In Pvd

Table 2 shows the values of turbulence degree of the PVD specimens with specific hydraulic gradients range under incremental confining pressures, which were calculated by employing Eq. (5). The values of hydraulic gradients and transmissivity were taken from the research conducted by [28].

Table 2 Values of turbulence degree for PVD specimens

Confining pressure, σ_c (kPa)	i_1	i_2	PVD-T3	PVD-T4	PVD-T5
20	1	0.5	0.61	0.80	0.57
	0.5	0.4	0.83	0.78	0.41
	0.4	0.2	0.63	0.56	0.60
50	1	0.5	0.51	0.74	0.62
	0.5	0.4	0.72	0.62	0.37
	0.4	0.2	0.73	0.85	0.76
100	1	0.5	0.53	0.73	0.62
	0.5	0.4	0.89	0.76	0.24
	0.4	0.2	0.91	0.88	0.84
150	1	0.5	0.98	0.75	0.66
	0.5	0.4	0.93	0.83	0.32
	0.4	0.2	0.81	0.89	0.84
200	1	0.5	0.88	0.70	0.68
	0.5	0.4	0.86	0.90	0.35
	0.4	0.2	0.90	0.93	0.82

The majority of the calculated values for the turbulence degree of PVD-T3, PVD-T4, and PVD-T5 ranged between 0.5 and 1.0, indicating a semi-turbulent flow condition. For PVD-T5, however, some turbulence degrees were found to be less than 0.5, indicating a turbulent flow condition. These results demonstrated that the degree of turbulence varied based on the particular hydraulic gradients applied.

In addition, the theory proposed by [25] supported these observations by suggesting that lower hydraulic gradients correspond to higher turbulence degrees. Furthermore, it was observed that as the confining pressure increased, the average turbulence degree also increased, indicating a decline in turbulence as the drainage area decreased.

Overall, these results reflect an understanding of the flow behavior within PVD systems under various hydraulic gradients and confining pressures, highlighting the intricate relationship between turbulence degree, hydraulic conditions, and drainage area.

6.3. Relationship Of Discharge Capacity And Confining Pressure

The relationship between PVD thickness and confining pressure for all specimens is shown in Fig. 5. The thickness values depicted on the graph are the average values derived from the research conducted by [14]. By analyzing these data, the relationship between the thickness (t_D) and the confining pressure (σ_c) can be determined, as shown by Equations (16) to (18). These equations provide a mathematical representation of the functional dependence between PVD thickness and confining pressure, thereby providing valuable insight into the behavior and efficacy of the PVD system under various confining pressures.

$$t_D = 0.0044\sigma_c^{-0{,}125} \text{ , for PVD-T3} \quad (16)$$

$$t_D = 0.0052\sigma_c^{-0{,}091} \text{ , for PVD-T4} \quad (17)$$

$$t_D = 0.0058\sigma_c^{-0{,}054} \text{ , for PVD-T5} \quad (18)$$

where t_D is PVD thickness (m), and s_c is confining pressure (kPa).

Figure 6 presents the relationship between the apparent velocity (v_{app}) and the confining pressure for PVD-T3, where v_{app} is calculated using Equation (6). The corresponding water discharge values (Q) were obtained through [14] research.

Equations (19) to (22) were derived in order to establish the relationships between apparent velocity and confining pressure. The values of hydraulic conductivity, which are dependent on the hydraulic gradient ($k_{(i)}$), were derived by substituting Equations (16-18) into Equation (9) with particular values of the hydraulic gradient. The relationship between k(i) and confining pressure for PVD-T3 can therefore be expressed using Equations (23) to (26).

$$v_{app} = 1.3265\sigma_c^{-0.361} \text{ , for } i\text{=1} \quad (19)$$

$$v_{app} = 0.9599\sigma_c^{-0.369} \text{ , for } i\text{=0.5} \quad (20)$$

$$v_{app} = 0.7363\sigma_c^{-0.353} \text{ , for } i\text{=0.4} \quad (21)$$

$$v_{app} = 0.5443\sigma_c^{-0.403} \text{ , for } i\text{=0.2} \quad (22)$$

$$k_{(i)} = 1.3265\sigma_c^{-0.361} \text{ , for } i\text{=1} \quad (23)$$

$$k_{(i)} = 1.9198\sigma_c^{-0.369} \text{ , for } i\text{=0.5} \quad (24)$$

$$k_{(i)} = 1.8408\sigma_c^{-0.353} \text{ , for } i\text{=0.4} \quad (25)$$

$$k_{(i)} = 2.7215\sigma_c^{-0.403} \text{ , for } i\text{=0.2} \quad (26)$$

PVD-T4 and PVD-T5 were investigated using the same methodology to determine the relationship between discharge capacity and confining pressure. The relationships between apparent velocity and confining pressure for PVD-T4 and PVD-T5 are illustrated in Figures 7 and 8, respectively. The equations for apparent velocity, hydraulic conductivity, and discharge capacity for each hydraulic gradient are shown in Table 3.

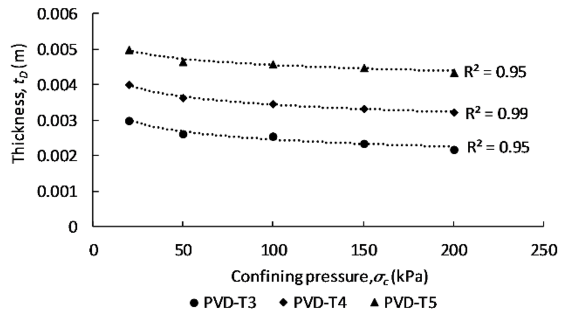

Figure 5 Relationship of PVD thickness and confining pressure.

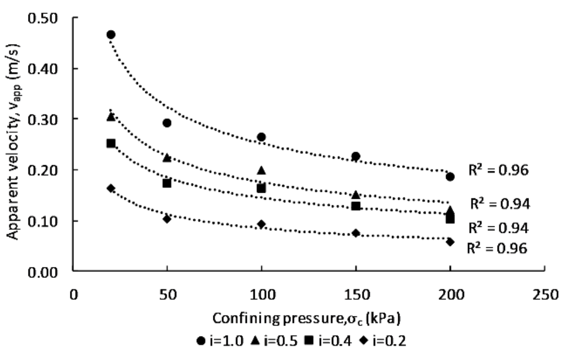

Figure 6 Relationship of apparent velocity and confining pressure of PVD-T3.

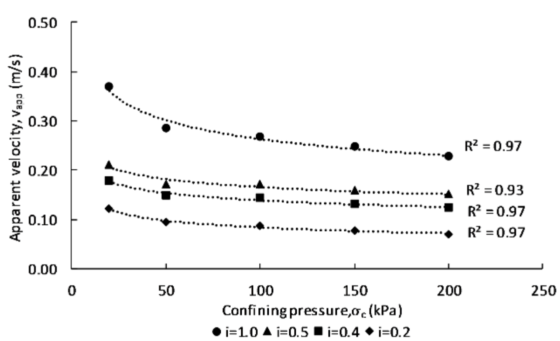

Figure 7 Relationship of apparent velocity and confining pressure of PVD-T4.

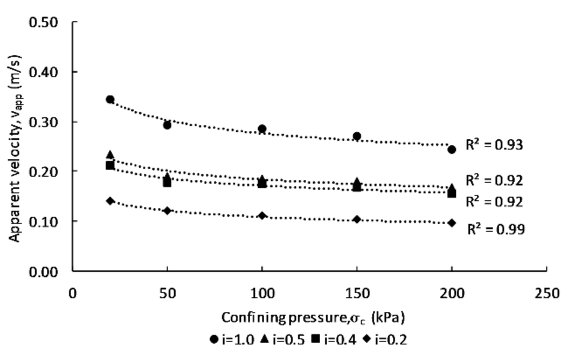

Figure 8 Relationship of apparent velocity and confining pressure of PVD-T5.

Table 3 Equations of hydraulic parameters of PVD-T4 and PVD-T5

Specimen	i	v_{app} (m/s)	$k_{(i)}$ (m/s)	q_w (m³/s)
PVD-T4	1.0	$0.6472\sigma_c^{-0.196}$	$0.6472\sigma_c^{-0.196}$	$\frac{3.3654\times10^{-4}}{\sigma_c^{0.287}}$
	0.5	$0.3084\sigma_c^{-0.135}$	$0.6168\sigma_c^{-0.135}$	$\frac{3.2074\times10^{-4}}{\sigma_c^{0.226}}$
	0.4	$0.276\sigma_c^{-0.149}$	$0.69\sigma_c^{-0.149}$	$\frac{3.588\times10^{-4}}{\sigma_c^{0.24}}$
	0.2	$0.2337\sigma_c^{-0.223}$	$1.1685\sigma_c^{-0.223}$	$\frac{1.1685\times10^{-4}}{\sigma_c^{0.314}}$
PVD-T5	1.0	$0.506\sigma_c^{-0.131}$	$0.506\sigma_c^{-0.131}$	$\frac{2.9348\times10^{-4}}{\sigma_c^{0.185}}$
	0.5	$0.3302\sigma_c^{-0.127}$	$0.6604\sigma_c^{-0.127}$	$\frac{3.8303\times10^{-4}}{\sigma_c^{0.181}}$
	0.4	$0.297\sigma_c^{-0.12}$	$0.7425\sigma_c^{-0.12}$	$\frac{4.3065\times10^{-4}}{\sigma_c^{0.174}}$
	0.2	$0.2254\sigma_c^{-0.159}$	$1.127\sigma_c^{-0.159}$	$\frac{6.5366\times10^{-4}}{\sigma_c^{0.213}}$

Therefore, the relation between discharge capacity (q_w) and confining pressure was established by substituting Eq. (16) and Eqs. (23) – (26) to Eq. (10), and finally yields Eqs. (27) to (30).

$$q_w = \frac{5.84\times10^{-4}}{\sigma_c^{0.476}}\text{, for } i = 1 \tag{27}$$

$$q_w = \frac{5.4471\times10^{-4}}{\sigma_c^{0.494}}\text{, for } i = 0.5 \tag{28}$$

$$q_w = \frac{8.0995\times10^{-4}}{\sigma_c^{0.478}}\text{, for } i = 0.4 \tag{29}$$

$$q_w = \frac{1.1935\times10^{-3}}{\sigma_c^{0.528}}\text{, for } i = 0.2 \tag{30}$$

To verify the accuracy of the proposed equations, a comparison was made between the discharge capacity values obtained from the equations and those generated from PVD-T3, PVD-T4, and PVD-T5 experimental tests. The consistency between the discharge capacity values determined by the equations and the experimental results is shown in Figs. 9 through 11. The discharge capacity under incremental confining pressures can therefore be accurately predicted using the equations proposed in this study.

Figures 9-11 establish clearly that the hydraulic gradient significantly influences the discharge capacity of PVDs. The curves demonstrate that the discharge capacity increases as the hydraulic gradient rises. This relationship has the greatest significance for PVDs with larger cross-sectional areas, where the influence of hydraulic gradient on discharge capacity is more pronounced. This finding suggests that PVDs with larger cross-sections are more resistant to variations in hydraulic gradient, which contributes to their enhanced ability to manage water flow.

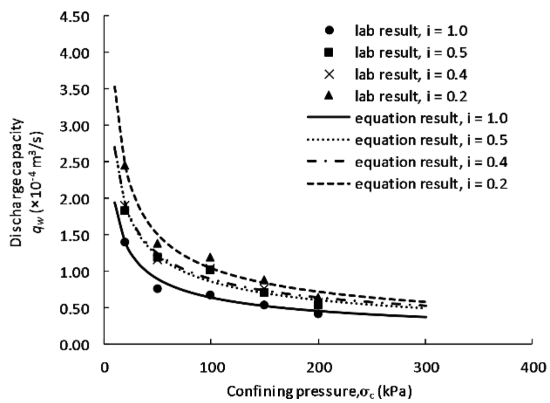

Figure 9. Comparison of theoretical and experimental values of discharge capacity for PVD-T3.

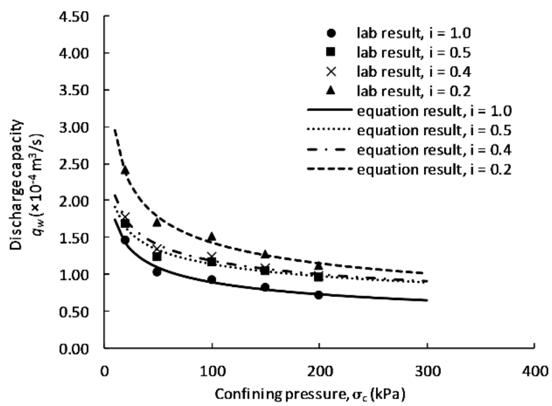

Figure 10. Comparison of theoretical and experimental values of discharge capacity for PVD-T4.

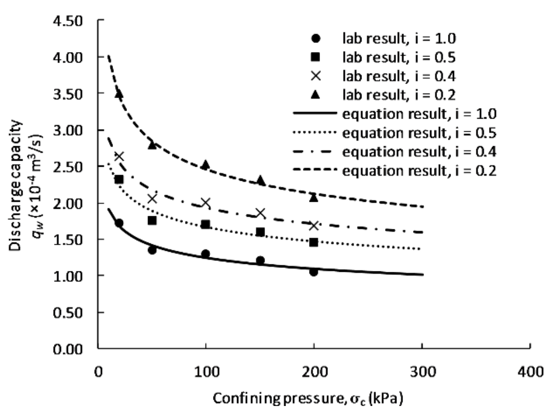

Figure 11. Comparison of theoretical and experimental values of discharge capacity for PVD-T5.

The observed effect of the hydraulic gradient can be attributed to alterations in flow conditions within PVDs. As the hydraulic gradient increases, so does the flow velocity within the PVDs, resulting in improved drainage and consolidation characteristics. Higher flow velocities assist in draining excess pore water from the surrounding soil, thereby reducing excess pore pressure and encouraging quicker soil consolidation. Additionally, the increased flow velocity provides to prevent clogging and sedimentation within the PVDs, ensuring sustained drainage performance.

The relationship between hydraulic gradient and PVD behavior is key to understanding and optimizing PVD systems' performance. The hydraulic gradient is the driving force behind water flow through the PVDs and plays an essential role in determining the system's discharge capacity and overall effectiveness.

It is necessary to comprehend the relationship between hydraulic gradient and PVD behavior to optimize the design and operation of PVD systems. Engineers can ensure the intended level of drainage and consolidation is achieved by carefully selecting the appropriate hydraulic gradient for a given project. In addition, this information can influence the design of PVD systems with optimal cross-sectional areas, taking into account the anticipated hydraulic gradients to optimize their performance.

The relationship between hydraulic gradient and PVD behavior can be investigated further through additional research and experiments. Investigating a broader range of hydraulic gradients and their effects on discharge capacity, consolidation rate, and soil stability will contribute to the improvement of PVD system design and implementation.

4.0 CONCLUSION

Three PVD samples of varying thicknesses were evaluated in the laboratory to evaluate their discharge capacity and transmissivity under different hydraulic gradients. The PVD was put through a series of incremental confining pressures ranging from 50 to 200 kPa. This study's instrument was designed in accordance with ASTM D4716.

The flow condition of PVDs was evaluated utilizing the limiting hydraulic gradient methodology. The results demonstrated that the flow within the PVD specimens was not laminar, indicating that non-laminar flow behavior must be considered in the design of PVD systems.

The study indicates a range of turbulence levels in the PVD-T3, PVD-T4, and PVD-T5 samples, indicating a semi-turbulent flow condition with some turbulence. Lower hydraulic gradients resulted in greater turbulence, confirming the effect of hydraulic gradients on turbulence magnitude. In addition, increasing confining pressure resulted in an increase in turbulence degree, indicating a decrease in turbulence in smaller drainage areas.

Under increasing confinement pressures, the proposed equations accurately predict the PVDs' discharge capacity. The comparison with experimental results revealed excellent consistency. The hydraulic gradient influences the discharge capacity considerably, particularly for PVDs with larger cross-sectional areas. Understanding the relationship between hydraulic gradient and PVD behavior is crucial for optimizing system design and accomplishing drainage and consolidation.

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