

Effect of Well Resistance on Time Factor Ratio Due to PVD Deformation

Galuh Chrismaningwang^{1,3*}, Hary Christady Hardiyatmo¹, Agus Darmawan Adi¹,
Teuku Faisal Fathani^{1,2}

¹ Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Yogyakarta, INDONESIA
Jl. Grafika No. 2 Kampus UGM, Yogyakarta

² Center for Disaster Mitigation and Technological Innovation (GAMA-InaTEK), Universitas Gadjah Mada, Yogyakarta, INDONESIA
Jl. Grafika No. 2 Kampus UGM, Yogyakarta

³ Department of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, INDONESIA
Jalan Ir. Sutami No. 36 A Surakarta

*Corresponding author: galuh.chrisma.n@mail.ugm.ac.id

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ABSTRACT One of the most common soft soil enhancement techniques used to expedite the consolidation time significantly is Prefabricated Vertical Drains (PVD). This technique needs a sufficient discharge capacity value because it primarily functions as a drainage channel. The deformation of PVD is considered as one of the primary factors which affect discharge capacity. Therefore, this research determined the influence of upper-side deformation on PVD's discharge capacity (q_w) using a specific design apparatus known as ASTM D4716, which manages the determination of transmissivity and flow rate at the longitudinal direction of geosynthetics. Furthermore, two PVD samples with dimensions of 3 and 4 mm thickness, 100 mm width, and 1000 mm length were examined under straight and buckled conditions. Stepwise confining pressures from 50 to 200 kPa were subjected to the samples under hydraulic gradients with values of 0.2, 0.5, and 1.0. The results showed that samples with greater thickness had higher discharge capacity, which significantly reduced in the lower hydraulic gradient. The deformation on the upper side of PVD induced a decrease of discharge capacity by approximately 13-16%, which led to a delay in the consolidation time. The discharge capacity values obtained from the experiments were employed as parameters in a time factor ratio of $T_{h,w}/T_h$. The analysis results show that the buckled PVD has a more considerable consolidation time due to the increase in the $T_{h,w}/T_h$ ratio, with a discharge capacity value below 10^{-4} m³/s. It can be concluded that the deformation in the form of buckled conditions on the upper side of PVD had a considerable impact on PVD effectiveness.

KEYWORDS Consolidation, Discharge capacity; Geosynthetics; Soil improvement; Transmissivity; Preloading.

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1 INTRODUCTION

One of the most popular methods of enhancing soft soil in Indonesia is by using Prefabricated Vertical Drains (PVD). According to a research carried out by Hansbo (1979), PVD functions by shortening the drainage path to accelerates the soft soil consolidation time. In infield practice, PVD is often used alone or in combination with surcharge preloading, vacuum preloading, or Prefabricated Horizontal Drains (PHD). This method is considered more practical and economical than other soil improvement methods (Zhang, Ye, and Xu, 2018; Da Silva *et al.*, 2017). The efficiency of PVD depends on its discharge capacity, which is influenced by several factors, such as the opening of drainage channel area, the lateral earth pressure, the soft soil infiltration process, which tends to induce a clogging inside the core, and its deformation (Holtz, 1987).

Koerner (2005) stated that a variety of environmental concerns influences the flow rate of PVD. Over the past decades, comprehensive studies have been carried out on the discharge capacity of PVD influenced by deformation and confining pressures (Hansbo, 1997; Indraratna and Chu, 2005). For instance, Hansbo (1997) stated that the drains embedded at a considerable depth had a low discharge capacity value, leading to a consolidation time increase. Studies have also been conducted on the discharge capacity of PVD or PHD using ASTM or modified triaxial test apparatus. Bo *et al.* (2016) conducted laboratory works to analyze the factors that influenced PVD discharge capacity using straight and buckled drain testing devices. The research found that the discharge capacity reduced when the vertical pressure and the hydraulic gradients increased, significantly

influencing hydraulic gradients on lower vertical pressure. Chrismaningwang *et al.* (2020) also carried out a research to determine the discharge capacity test using ASTM D4716 device and a short-term vertical pressure test using several types of PVD and PHD. The test results showed that PVD was more resistant to confining pressure compared to PHD. Furthermore, under 200 kPa confining pressure, the discharge capacity of PHD was reduced by over 90%. Jang *et al.* (2015) evaluated the influence of calcium carbonate filtration on the discharge capacity of geocomposite and various types of PVD using a discharge capacity test device modified from a triaxial test. The results showed that a harmonica-shaped core provided higher discharge capacity than the reformed.

Studies on the effect of PVD deformation have also been extensively conducted, which concluded that the decrease in discharge capacity was reliant on the drain structure. Ali (1991) investigated the flow behavior of deformed PVD by combining the influence of lateral pressure and deformation of soil. The research showed that the discharge capacity reduction was affected by its geometrical structure and bending rigidity, while PVD with greater filter stiffness had better performance due to its resistance to lateral pressure. This research also concluded that the discharge capacity of PVD does not need to be established using the result of straight PVD since a large settlement tends to generate PVD deformation. Jeon (2014) conducted a short-term transmissivity test on bi-planar and tri-planar geonets. The results showed that the decrease of discharge capacity was determined by the structure of the geonet, with those comprising greater thickness had lower discharge capacity reduction. The results also showed that the decrease of geonet discharge capacity was significant when subjected to a pressure greater than 600 kPa. Tran-Nguyen *et al.* (2010) studied the impact of deformation on four types of PVD's discharge capacity with two types of soil as confining medium by conducting a laboratory measurement. Tran-Nguyen stated that for a project with a considerable settlement, the value

of discharge capacity used on design is not solely dependent on the discharge capacity of straight PVD. The test also exhibited that hydraulic gradients were critically affected by discharge capacity reduction due to its influence on the type of water flow inside the PVD core. Cai *et al.* (2017) carried out a research on the experimental test results on deformed PVD installed in dredged soil with vacuum preloading. The vacuum pressure distribution on PVD has a bilinear relationship with the PVD deformation. On the other hand, research on upper-side PVD deformation with an extension above the soil has never been conducted. Therefore, this study examines the influence of upper-side deformation on the well resistance of PVD.

The buckled deformation imitated PVD condition is always buckled in the upper-side when worked alone or in combination with PHD. The value of PVD's well resistance was defined by measuring its discharge capacity, which is determined indirectly by conducting a laboratory measurement and using an apparatus designed according to ASTM D4716. It is also a method used to resolve the value of discharge capacity, transmissivity, and in-plane permeability of PVD by applying confining pressure under constant head flow conditions.

2 DISCHARGE CAPACITY

Discharge capacity (q_w), is represented as the quantity of water discharge in the longitudinal directions with a particular hydraulic gradient (i) per unit time (Hansbo, 1979). According to Bourge's-Gastaud, Blond, and Touze-Foltz (2013), Tripathi and Nagesha (2010), it is considered the most critical parameter in vertical drainage design and performance. Furthermore, Chung, Kweon, and Jang (2014) stated that the inaccurate estimation of consolidation rate is due to the incorrect input of discharge capacity value. Discharge capacity and the hydraulic gradient are defined in Equations (1) and (2).

$$q_w = \frac{Q}{i} \quad (1)$$

$$i = \frac{\Delta h}{L} \quad (2)$$

where, Q denotes the rate of water flow within each unit of time (m^3/s), i is the hydraulic gradient, Δh is the difference of water head (m), and L is the drainage length (m). In addition, L is characterized as the specimen length.

The effectiveness of soil improvement using PVD depends on its discharge capacity, which needs to have a higher value than the surrounding soil's permeability value (Cascone and Biondi, 2013). Therefore, the closer the discharge capacity value to the soil's permeability, the greater the consolidation time. The value of well resistance depends on k_h/q_w , with the suggested values of required discharge capacity ($q_{w(\text{req})}$) higher than 3.2×10^{-6} to $4.8 \times 10^{-6} \text{ m}^3/\text{s}$ (Holtz *et al.*, 1991). The value of $q_{w(\text{req})}$ is defined in Equation (3), which was recommended by Mesri and Lo (1991).

$$q_{w(\text{req})} = 5k_h L^2 \quad (3)$$

where, k_h is the surrounding soil's horizontal permeability (m/s), and L is the maximum drainage flow length (m).

3 WELL RESISTANCE

Well resistance is the product of horizontal soil permeability and discharge capacity (k_h/q_w) function. The influence escalates when the value of discharge capacity reduces, which lead to a consolidation time increment, t , defined as a function of $\frac{T_h D^2}{c_h}$, where T_h is the factor of time,

D is the influence diameter value of 1.05 S for a triangular PVD formation or 1.13 S for a rectangular PVD formation, S is the distance between each PVD, and c_h is the coefficient of horizontal consolidation. The value of the time factor is determined by using Equations (4) and (5), proposed by Barron (1948) and Hansbo (1979), respectively.

$$T_h = \frac{\ln(1-U)F(n)}{-8} \quad (4)$$

$$T_{h,w} = \frac{\ln(1-U)F_w(n)}{-8} \quad (5)$$

U denotes the consolidation degree, $F(n)$ is a drain spacing factor, and $F_w(n)$ is a drain spacing factor that incorporates well resistance. The time factor ratio is used to determine the increase of consolidation time due to well resistance. The value of $T_{h,w}/T_h$ is calculated by using Equation (6) proposed by Tran-Nguyen, Edil, and Schneider (2010), which was derived from the vertical drainage theory proposed by Hansbo (1979).

$$\frac{T_{h,w}}{T_h} = 1 + \frac{(2\pi/3)L^2(k_h/q_w)}{\ln(n)-3/4} \quad (6)$$

where, n is D/d_w , and d_w is the equivalent diameter.

4 RESEARCH METHODS

4.1 The Structure of PVD

PVD is a geocomposite material consisting of a filter made from geotextile and a core made from polymer. The filter is used to protect the core from soft soil infiltration, which clogs inside the drain, leading to decreased discharge capacity (Jang, Kim, and Lee, 2015). This research examined the discharge capacity of PVD-A and PVD-B harmonica cored samples, with the dimensions of 3 and 4 mm thickness (t) and 100 mm width (w). The physic and mechanic characteristics of the drains are shown in Table 1.

4.2 Methods and Test Apparatus

This research utilized a specific apparatus developed by Chrismaningwang *et al.* (2020) to evaluate the PVD-PHD connection system's discharge capacity by adopting ASTM D4716, which discusses geosynthetic transmissivity (ASTM, 2001). The apparatus was designed to represent the field condition, where the lateral earth pressure confines the PVD and PHD, and surcharge preloading, respectively.

Table 1. Physic and mechanic characteristics of PVD

Characteristics	Testing standards	PVD-A	PVD-B
Composite			
Thickness, t (mm)	ASTM D5199-99	3	4
Width, w (mm)	ASTM D5199-99	100	100
Tensile strength (kN/m)	ASTM D4595	2.53	2.55
Filter			
		Polyethylene terephthalate	Polyethylene terephthalate
Thickness (mm)	ASTM D5199-99	0.24-0.25	0.24-0.25
Permeability (mm/s)	ASTM D4491	0.347	0.358
AOS (μm)	ASTM D4751	75-90	75-90
Core			
		Polypropylene	Polypropylene
Mass per unit area, μ (kg/m ²)	ASTM D5261-92	0.48	0.52
Elongation at break (%)	ASTM D4632	46	45
Polymer density, ρ (kg/m ³)	ASTM D5261-92	898.54	898.54

The test apparatus consisted of two main parts, namely cylinder and upper compression chambers. The cylinder compression chamber was made of 10 mm thick acrylic with 200 mm diameter and 500 mm height, complete with two steel pedestals and PVD holders. The confining pressure mechanism in this chamber implemented pressured water controlled by a constant device. The upper compression chamber was made from 10 mm thick steel with 470 × 460 × 700 mm and used as an outflow reservoir. The illustration of the apparatus is shown in Figure 1.

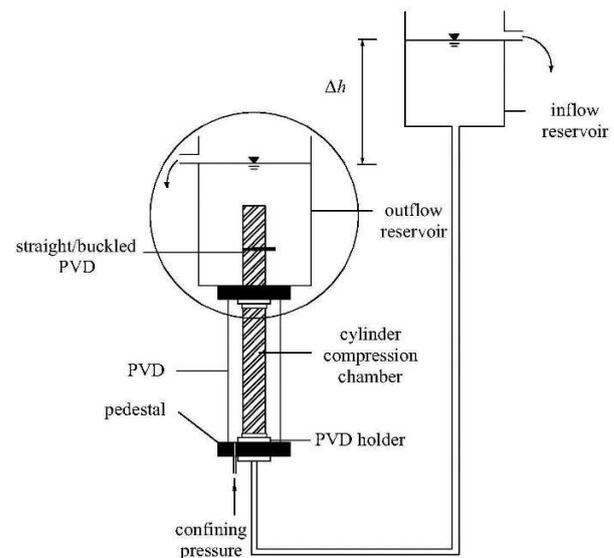
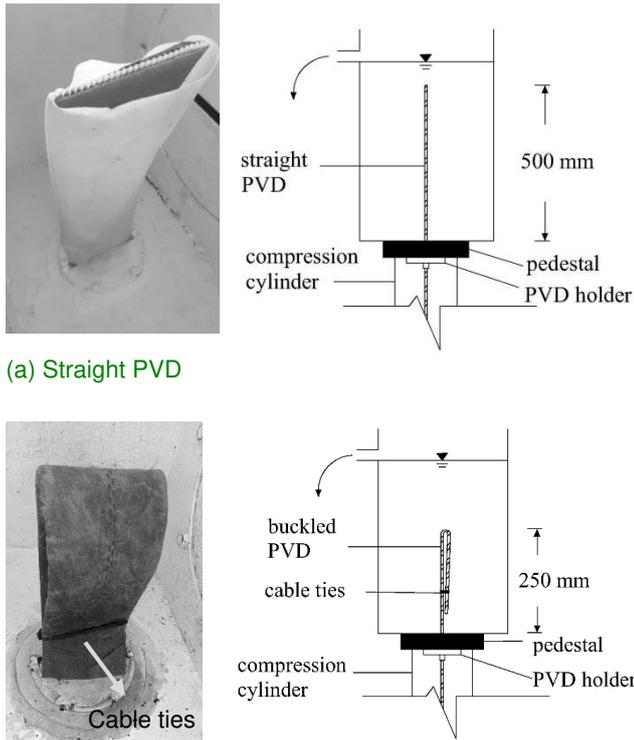


Figure 1. Illustration of the discharge capacity test apparatus (modified from Chrismaningwang *et al.*, 2020b).

Comprehensive studies have been carried out to determine the effect of PVD deformation on discharge capacity (Ali, 1991; Jang, Kim and Lee, 2015; Bo *et al.*, 2016). In infield practice, PVD deformation is a result of lateral earth pressure or soil preloading. This study focused on PVD deformation above the soil surface, buckled due to the soil preloading pressure or connection to PHD. All tests were conducted in 1 m length specimens using straight and buckled (tied with a cable tie) conditions on the upper side, as shown in Figure 2. The straight specimens are identified as PVD-A-St and PVD-B-St, while the buckled ones are PVD-A-Bc and PVD-B-Bc.

The specimens' setting is as follows: 500 mm length specimens were placed in the cylinder compression chamber, and the rest were extended to the box compression chamber. The buckled condition was obtained by folding the PVD at the height of 250 mm inside the outlet tank. Meanwhile, for the straight condition, it was kept at the initial position. All of the specimens were wrapped in latex membranes to separate them from the confining water. It was further subjected to stepwise confining pressures at a range of 50-200 kPa, with a 50 kPa addition at every loading stage. The water flow mechanism is a constant head flow, and the variation of hydraulic gradient was acquired by adjusting the inlet tank.



(a) Straight PVD

(b) Buckled PVD

Figure 2. Detail of outflow reservoir and sample configuration

A calibration test is used to determine a calibration curve that originated from the relationship of the flow rates and the head difference (ASTM, 2001). A calibration curve is a reference used to resolve the calibrated head difference (Δh_{cal}), needed to determine the value of the corrected hydraulic gradient (i_{corr}). Chrismaningwang *et al.* (2020) carried out a research on the apparatus's calibration test and determined Δh_{cal} using Equation (7).

$$\Delta h_{cal} = 0,0025Q^{1,7163} \tag{7}$$

The value of i_{corr} is determined using Miura and Chai (2015) research as stated in Equation (8):

$$i_{corr} = \frac{\Delta h - \Delta h_{cal}}{L} \tag{8}$$

The calculation showed that the values of Δh_{cal} were noticeably small (between 8.9×10^{-11} to 8.9×10^{-10} m) hence the insignificant effect of the apparatus on the specimen's in-plane flow indicates that the apparatus is eligible.

5 RESULTS AND DISCUSSIONS

5.1 The Effect of Confining pressure (σ_c) on The Discharge Capacity of Deformed PVD

Figures 3 and 4 show the decline in discharge capacity due to the stepwise confining pressure under varied hydraulic gradients. The values of discharge capacity and i_{corr} were obtained from Equations (1) and (8). According to preliminary studies, identical curve patterns were noticed for all specimens, with a decline in the discharge capacity due to the confining pressure (Yarahmadi, Gratchev, and Jeng, 2017; Chai *et al.*, 1995). Meanwhile, the confining pressure escalated from 50 to 200 kPa. The average values of q_w reduction for PVD-A-St, PVD-A-Bc, PVD-B-St, and PVD-B-Bc are 62.54%, 64.90%, 42.37%, and 40.49%, respectively. The decrease of discharge capacity value is more critical when the hydraulic gradient is low in accordance with the theory proposed by preliminary studies (Bergado, Manivannan, and Balasubramaniam, 1996; Bo *et al.*, 2016).

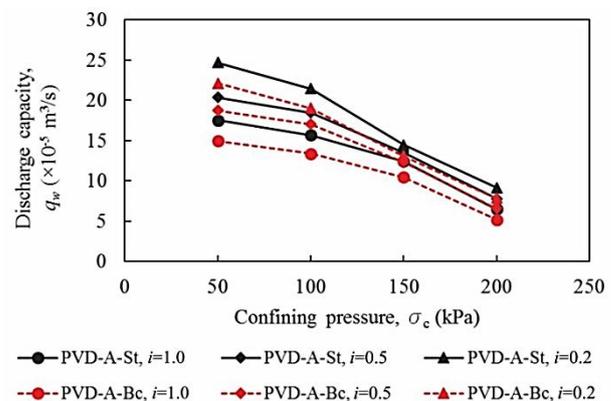


Figure 3. Discharge capacity values of PVD-A.

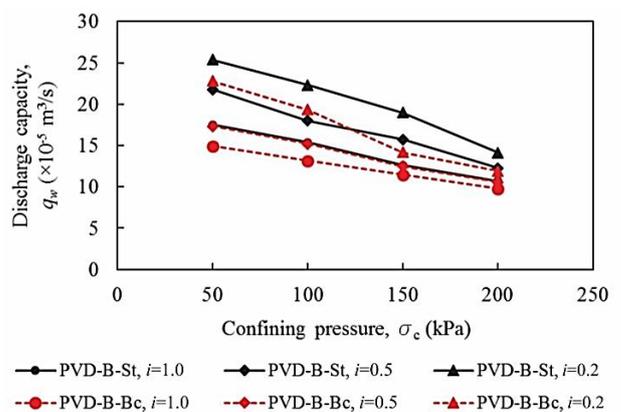


Figure 4. Discharge capacity values of PVD-B.

The test results showed that the discharge capacity is higher on the straight samples. Furthermore, when the PVD-A and PVD-B were buckled by 16.24% and 13.09%, the whole drainage area was obstructed, thereby leading to a discharge capacity reduction. Both specimens had the same filter and core material, although the PVD-B had higher discharge capacity values, presumably because the stiffness is more significant with greater thickness, which congenial with preliminary studies (Chai, Miura, and Nomura, 2004; Miura and Chai, 2015). These results showed that the thicker PVD were more resistant to confining pressure and deformation. However, all of the specimens were fulfill the criteria by having a q_w value higher than $q_{w(req)}$, which are 3.2×10^{-6} to 4.8×10^{-6} m³/s (Holtz, 1987; Bo, 2004; Chu, Bo, and Choa, 2004).

5.2 Time Factors Ratio Analysis ($T_{h,w}/T_h$)

The discharge capacity value is compulsory to determine the value of well resistance, which is used as a parameter in vertical drainage design. According to Holtz (1987), the well resistance reduces with a decrease in discharge capacity and an increase in consolidation time. The time factor ratio analysis is convenient to measure the consolidation time delay, which is influenced by well resistance. The values of discharge capacity acquired from the laboratory measurement were used to determine the time factors ratio, $T_{h,w}/T_h$, by applying Equation (6). The time factors ratio analysis was conducted under several assumptions:

- a) the horizontal permeability of surrounding soil (k_h) is 1×10^{-8} m/s,
- b) the length of embedded PVD (L) is 20 m,
- c) with 1 m spacing (S) and triangular formation.

The relation between the drains' discharge capacity and the time factors ratio for straight and buckled PVD are shown in Figures 5 and 6,

respectively. The buckled PVD has a more considerable consolidation time because of the higher $T_{h,w}/T_h$ ratio, while those with greater thickness provided a lower time factors ratio. The increase in time factors ratio was more prominent in the buckled specimens, while those for the straight specimens are linear and smooth. The values of $T_{h,w}/T_h$ for all specimens are plotted in Figure 7. Moreover, the value of $q_{w(req)}$ obtained from Equation (3) applied on Equation (6) gave the value of $T_{h,w}/T_h = 1.19$. The analysis results showed that the increase in the time factor ratio was significant on PVD with a discharge capacity value less than 10^{-4} m³/s. Therefore, it is concluded that the deformation on the upper side of PVD had a considerable effect on PVD performance.

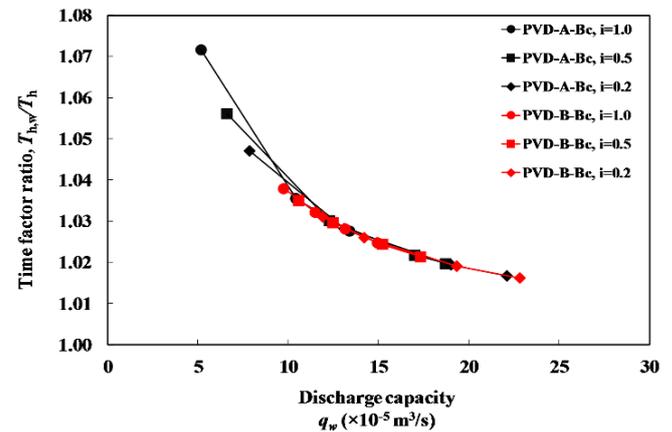


Figure 5. Ratio of $T_{h,w}/T_h$ on straight PVD

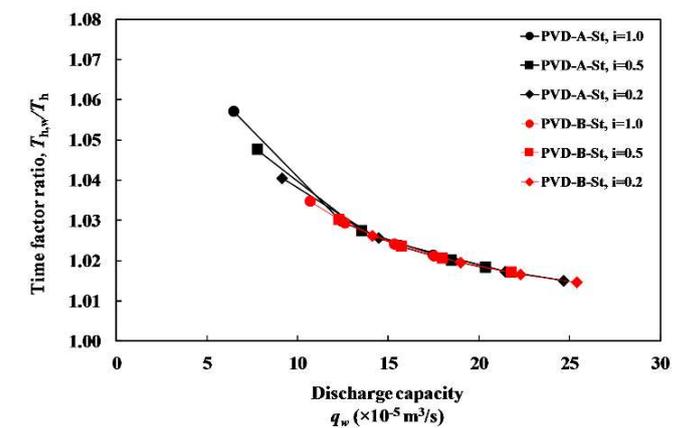


Figure 6. Ratio of $T_{h,w}/T_h$ on buckled PVD.

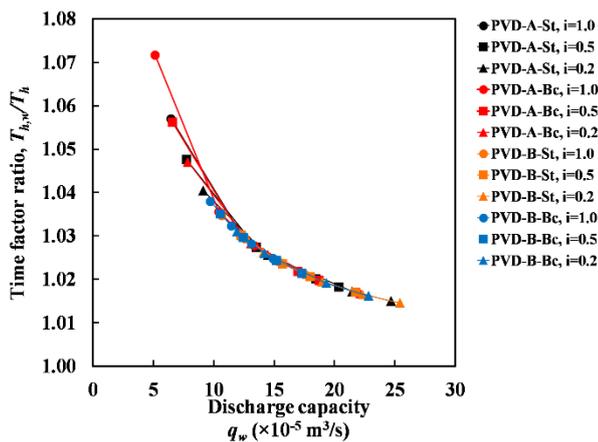


Figure 7. Ratio of $T_{h,w}/T_h$ as a function of q_w .

6 CONCLUSIONS

The discharge capacity is the key variable that defines PVD behavior considered in the calculation of well resistance, taken into account in the vertical drainage design. This study adopted ASTM D4716 to evaluate the significance of confining pressure and buckled deformation on PVD specimens' discharge capacity with different thicknesses to simulate infield practice conditions.

The test results showed that the thicker samples have higher discharge capacity with more critical reduction at lower hydraulic gradients. Straight PVD-A, buckled PVD-A, straight PVD-B, and buckled PVD-B have average q_w reduction values of 62.54%, 64.90%, 42.37%, and 40.49%, respectively. The buckled specimens' discharge capacity is lower than the straight by approximately 13-16%, thereby confirming that the deformation on the upper-side of PVD affected its performance. Nonetheless, all of the specimens were considered eligible as vertical drainage since the value of q_w is larger than $q_{w(req)}$.

The q_w values obtained from the experiments were employed as a parameter in a time factor ratio $T_{h,w}/T_h$ analysis. The results showed that the deformed PVD has a higher time factor ratio, thereby leading to a consolidation time delay.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the corresponding author.

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