Investigation of Geometric and Smear Parameters in the Design of Prefabricated Vertical Drains in Manila Bay

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Abstract. Prefabricated Vertical Drains (PVDs) are geosynthetic drains that are used to shorten the horizontal drainage path and allow water to flow laterally to the nearest drain. Because of remolding during installation, a zone of smear around the drain is formed, reducing the coefficient of horizontal permeability, and thus increasing time needed for consolidation. A sensitivity analysis was conducted to study the effects of varying PVD drain spacing, configuration, and smear properties in a multi-staged embankment using a soil profile in Manila Bay. A higher benefit in terms of increased maximum settlements is achieved when decreasing larger drain spacings as opposed to decreasing smaller drain spacings. However, the opposite is true for reduced consolidation times, wherein a higher benefit is achieved when decreasing smaller drain spacings as opposed to decreasing larger drain spacings. Meanwhile, a triangular configuration yields higher maximum settlements and lower consolidation times compared to that of a square configuration, with an average reduction in consolidation times of 32%. Additionally, a higher benefit in terms of increased settlement and reduced consolidation times is observed across all cases for smaller ratios of d_s/d and k_h/k_s corresponding to the ratio of the diameter of the smear zone and the drain, and the ratio of the horizontal permeability of undisturbed soil and the smear zone, respectively. Changing the drain spacing has the largest effect in consolidation times, with an average reduction of 77.69%. This is then followed by the smear properties k_h/k_s and d_s/d, with an average reduction of 58.03% and 49.84% respectively. The study reveals that an ideal drain design in terms of higher settlements and reduced consolidation times has a spacing of between 0.75 m and 1.0 m, triangular configuration, and installed with drain installation procedures that yield low d_s/d and k_h/k_s ratios.

Keywords: PVD · Smear · Consolidation · Drain Spacing · Drain Configuration

1 Introduction

In the Philippines, the demand for construction infrastructure projects is rising, driven by initiatives to develop the country's energy and transportation sectors (GlobalData, 2020). With this rise in construction development, it is unavoidable that some projects would be located on soft soils with undesirable properties such as low bearing capacity and low

R. E. Hammah et al. (Eds.): RIC 2023, AHE 19, pp. 425–431, 2023.
https://doi.org/10.2991/978-94-6463-258-3_42

shear strength, which might result to excessive settlement during the construction phase (Muhammad, et al., 2016). To remedy this, ground improvement techniques such as the use of prefabricated vertical drains (PVDs) are employed to ensure that the soil would be fit for construction use. Provision of these PVDs shortens the drainage paths, allowing pore water to flow laterally to the nearest drain which reduces time of consolidation.

During installation, soil surrounding the PVD is disturbed due to the action of the mandrel, forming a zone in which decreased permeability and increased compressibility can be observed (Hansbo, 1981). This slows down the flow of pore water into the drain and thus increases the time required for consolidation. This disturbed zone is composed of the smear zone, the zone of soil immediately adjacent the drain with reduced hydraulic conductivity, and the transition zone, the zone of soil which separates the smear and the undisturbed zones of the soil and exhibits decreasing degree of disturbance as distance from the drain is increased (Basu & Prezzi, 2007). The presence of the smear zone becomes an important consideration in the selection of PVD spacing, especially since using very close PVD spacing doesn't necessarily mean efficient increase in consolidation rates and settlement times. In the study by Saye (2001), the additional cost of PVD installation closer than 1.75 m has a limited benefit in hastening the time to reach the required degree of consolidation. This implies the presence of a lower-bound drain spacing limit, wherein any drain spacing closer than this limit would not yield a significant increase in consolidation rates. This may be explained by the overlapping of smear zones, which happens when the ratio of the diameters of the smear zone and the drain n is less than the ratio of the diameters of the smear zone and the drains. Interaction between the smear zones would cause a decrease in hydraulic conductivity and will thus impact the rate of consolidation (Walker & Indraratna, 2007).

It is then desired that the effect of varying drain spacing to the rate of consolidation be investigated to obtain the best combination of drain spacing and configuration that provides the optimal degree of consolidation. Specifically, this study seeks to investigate the effect of varying drain spacing and configuration to the rate of consolidation through *Rocscience Settle3* while taking into consideration the effects of smear zone properties, ratios d_s/d and k_h/k_s.

2 Methodology

Soil properties such as unit weights, compression indices, coefficients of permeability, and initial void ratio were obtained from borehole log data taken from locations at Manila Bay, which is known to have soils of low bearing capacity (Dungca, et. al., 2017), which makes it ideal as a soil model for ground improvement.

The embankment used for the model is the same test embankment used by Bergado, et. al. (2002) in their study in the application of PVDs on soft clay. It is a 40 m by 40 m staged embankment, with side slopes of 3H:1V, fill material compacted to an average bulk unit weight of 18 kN/m^3 and consists of four stages in a span of roughly 250 days.

A 100 mm by 5 mm band-shaped PVD with a length of 12 m was used for the model, taken from Al-Soud (2016) and Bergado, et. al. (2002) which use the same set of PVD measurements. Discharge capacity is kept at 20 m^3/d. Drains would be installed right before the first stage of the embankment is applied.

After modelling the soil and embankment in *Settle3*, PVDs with varying drain spacing, configuration, and smear properties were applied. The drain spacings were varied from 0.25 m to 3 m, in increments of 0.25 m, for a total of 12 drain spacings. The drain configuration used is both triangular and square patterns. For the smear properties, the ratios d_s/d and k_h/k_s were both varied from 1 to 10 in increments of 1. Initial model validation and calibration showed good agreement against the study of Al-Soud (2016).

Through *Settle3* consolidation settlement is determined as

$$\partial_i = \partial_{i+1} + \varepsilon_i h_i \tag{1}$$

And note that the calculation of vertical strain ε depends on the type of soil material used in the analysis. Meanwhile, vertical consolidation is governed by Terzaghi's 1D consolidation equation

$$\frac{\partial u}{\partial t} = \mathrm{c_v} \frac{\partial^2 u_e}{\partial z^2} \tag{2}$$

Discretization in time and space of the preceding equation yields

$$\frac{\partial u}{\partial t} = \frac{u_{i,t+\Delta t} - u_{i,t}}{\Delta t} \tag{3}$$

$$\mathrm{c_v} \frac{\partial^2 u_e}{\partial z^2} = \frac{c_v}{2(\Delta h)^2}\left[u_{ei-1,t} - 2u_{ei,t} + u_{ei+1,t} + u_{ei-1,t+\Delta t} - 2u_{ei,t+\Delta t} + u_{ei+1,t+\Delta t}\right] \tag{4}$$

The boundary conditions are applied depending on whether the boundaries are drained or undrained. *Settle3* uses both explicit and implicit methods to calculate pore pressures for each time stage, which provides the benefit of faster calculation without any loss of accuracy. Nodes were generated throughout the soil model for calculation of settlement and degree of consolidation. A query point is placed at the soil surface beneath the center of the embankment to obtain settlement and degree of consolidation data at this point. Plots of these data with respect to time were then obtained from this query point, beginning from time at end of construction of embankment stage 4 (t = 220 days) and ending at time t = 5000 days. The time at which 60% degree of consolidation is reached (T60) is then obtained using linear interpolation.

The T60 values obtained were analyzed with respect to the drain spacing, configuration, and smear properties d_s/d and k_h/k_s. The optimal properties were observed by checking which parameters affect the consolidation times the most. The trends observed from the results were then checked for validity by comparison with the T60 values using two different sets of soil properties.

3 Results and Discussion

3.1 Effect of Varying Drain Spacing

It was observed that the overall settlement throughout the soil surface beneath the embankment at end of analysis (t = 5000 days) increases as the spacing is decreased as seen in Fig. 1. An increase of approximately 14.41% in the maximum settlement can be

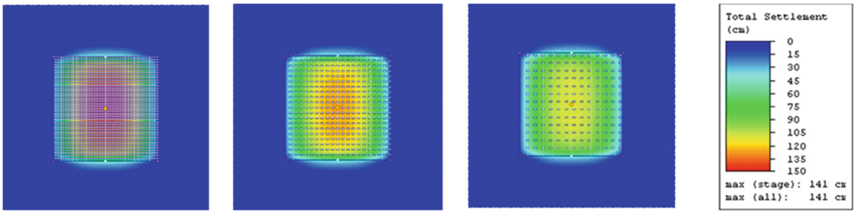

Fig. 1. Settlements at varying spacing (Left) 1 m (Center) 2 m (Right) 3 m

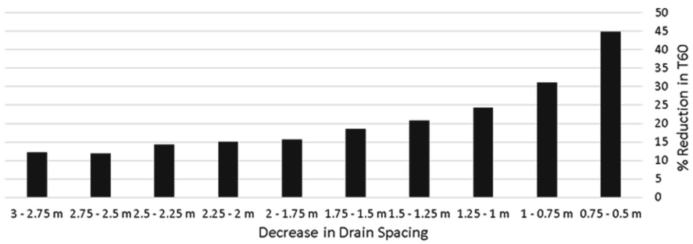

Fig. 2. Percent reduction in T60 vs reduction in drain spacing

observed from decreasing the spacing from 3 m to 2 m, while an increase of approximately 11.02% in the maximum settlement was observed when decreasing the spacing from 2 m to 1 m. This suggests that the benefit of added settlement when decreasing spacing is greater if decreasing from a larger drain spacing (from 3 m to 2 m), than if decreasing from a smaller spacing (from 2m to 1 m).

When considering the percent reduction in consolidation times between each succeeding drain spacing, larger reduction in consolidation times occur for smaller drain spacings than for larger drain spacings. To further observe this, the percent reduction in T60 for each succeeding drain spacings is shown in Fig. 2.

Calculation of the average reduction in consolidation times for all cases yielded an average reduction of 61.33% when decreasing from 2 m to 1 m, while an average reduction of 42.30% occur when decreasing from 3 m to 2 m.

3.2 Effect of Varying Drain Configuration

Notice in Fig. 3 (Left) that the settlements produced by the triangular configuration is consistently greater than that of the square one, except for the 0.25 and 0.5 m wherein the settlements are almost equal. It can also be noticed that the difference between settlements of triangular and square configurations increases with the drain spacing.

Meanwhile, for the consolidation times as shown in Fig. 3 (Right), cases with triangular configuration have a consistently lower T60 value than that of square cases. This means that the consolidation process is faster for a triangular pattern than for a square pattern. Like the observation in the earlier graph, the gap between the triangular and square cases seem to increase with the drain spacing, with almost equal settlements at the lower drain spacings (for 0.25 and 0.5 m). This behavior is consistent throughout all

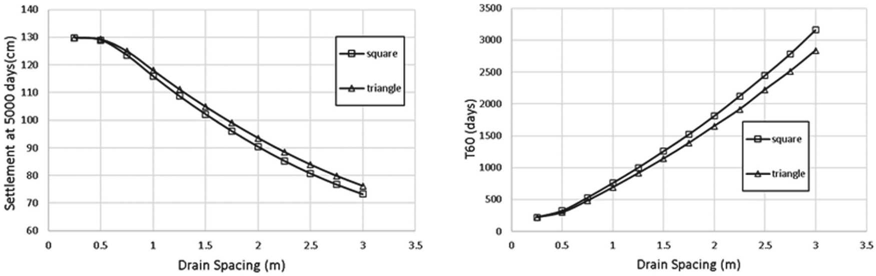

Fig. 3. (Left) Settlement vs drain spacing at t = 5000 days (Right) T60 vs drain spacing

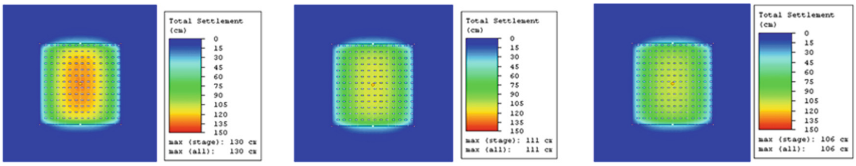

Fig. 4. Settlements at (Left) $d_s/d = 1$ (Center) $d_s/d = 5$ (Right) $d_s/d = 10$

cases, and calculation of the average reduction in T60 for all cases when changing the configuration from square to triangular yielded an average reduction of 31.99%.

3.3 Effect of Varying d_s/d

It has been observed that the maximum settlement decreases as the ratio d_s/d is increased as seen in Fig. 4. Approximately 14.62% decrease in maximum settlement is observed from $d_s/d = 1$ to $d_s/d = 5$, while approximately 4.5% decrease from $d_s/d = 5$ to $d_s/d = 10$. This means that the effect of decrease in maximum settlement is larger for smaller ds/d ratios (from 1 to 5) than for larger d_s/d ratios (from 5 to 10). Logically, the opposite is also true, wherein the effect of increase in maximum settlement is larger for smaller d_s/d ratios (from 5 to 1) than for larger d_s/d ratios (from 10 to 5).

Calculation of the average decrease in T60 value for all cases when decreasing d_s/d yielded an average reduction of 4.88% when decreasing the ratio from 10 to 5, and an average reduction of 52.18% was obtained when decreasing the ratio from 5 to 1. This further shows that the effect of reduction in consolidation times is larger for smaller d_s/d ratios (from 5 to 1) than for larger d_s/d ratios (from 10 to 5).

3.4 Effect of Varying k_h/k_s

Notice in Fig. 5, the maximum settlements decrease as k_h/k_s increases, with an approximately 14.62% decrease in maximum settlement for increasing k_h/k_s from 1 to 5, and approximately 11.44% decrease from $k_h/k_s = 5$ to 10. This trend is similar to the effect discussed earlier, wherein the effect of decrease in maximum settlement is larger for smaller k_h/k_s ratios (from 1 to 5) than for larger k_h/k_s ratios (from 5 to 10). Again mathematically, the opposite is also true, wherein the effect of increase in maximum

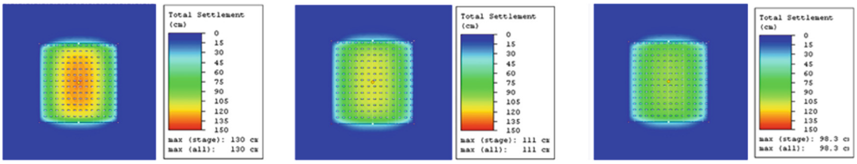

Fig. 5. Settlements at (Left) $k_h/k_s = 1$ (Center) $k_h/k_s = 5$ (Right) $k_h/k_s = 10$

settlement is larger for smaller k_h/k_s ratios (from 5 to 1) than for larger k_h/k_s ratios (from 10 to 5).

Calculation of the average decrease in T60 value for all cases when decreasing k_h/k_s yielded an average reduction of 18.16% when decreasing the ratio from 10 to 5, and an average reduction of 48.72% was obtained when decreasing the ratio from 5 to 1. This further shows that the effect of reduction in consolidation times is larger for smaller k_h/k_s ratios (from 5 to 1) than for larger k_h/k_s ratios (from 10 to 5).

4 Conclusions

The effect of drain spacing, configuration, and smear properties d_s/d and k_h/k_s to the consolidation rate is studied using the software *Rocscience Settle3*. A higher benefit in terms of increased maximum settlements is achieved when decreasing larger drain spacings as opposed to decreasing smaller drain spacings. However, the opposite is true for reduced consolidation times, wherein a higher benefit is achieved when decreasing smaller drain spacings (with an average reduction of 61.33% for decreasing spacing from 2 m to 1 m) as opposed to decreasing larger drain spacings (with an average reduction of 42.30% for decreasing spacing from 3 m to 2 m). Meanwhile, a triangular configuration yields higher maximum settlements and lower consolidation times compared to that of a square configuration, with an average reduction in consolidation times of approximately 32% when changing configuration from square to triangular.

Additionally, a higher benefit in terms of increased settlement and reduced consolidation times is observed across all cases for smaller ratios of d_s/d and k_h/k_s. The benefit of decreasing d_s/d and k_h/k_s is larger for smaller ratios of d_s/d and k_h/k_s.

Changing the drain spacing has the largest effect in consolidation times, with an average reduction of 77.69%. This is then followed by the smear properties k_h/k_s and d_s/d, with an average reduction of 58.03% and 49.84% respectively. The parameter with the least effect is configuration, but still provides a significant reduction in consolidation times (with an average reduction of approximately 32%) when configuration is changed from square to triangular.

A lower drain spacing reduces consolidation times but requires a larger number of drains. Meanwhile, a higher drain spacing yields longer consolidation times but requires lower number of drains. A balance between the benefit in consolidation times and number of drains must be achieved, and both of this is satisfied by the drain spacing ranging between 0.75 m and 1 m. Thus, an ideal drain design in terms of higher settlements and reduced consolidation times has a spacing of between 0.75 m and 1.0 m, triangular configuration, and installed with drain installation procedures that yields a low d_s/d and k_h/k_s ratio.

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