Use of Prefabricated Vertical Drain to Expedite the Consolidation Settlement

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Synopsis: The consolidation process of a thick soft clay layer takes long time to complete. To expedite the consolidation process, one of the effective measures is to shorten the drainage path. Prefabricated Vertical Drain (PVD) which usually has a plastic core enclosed in a non-woven geotextile filter jacket is designed and manufactured to allow water flow freely. Once the PVD is installed, the excess pore water pressure in soft clay can escape not only in the vertical direction but also in horizontal direction towards the PVD and flow along the PVD to a drainage blanket on ground surface or to other highly permeable soil layer at deeper depth. This paper provides a general review of the use of PVD. The characteristics, common types of PVD and the consolidation theories are briefly described. The design of PVD is discussed. Factors affecting the performance of PVD are also discussed. Lastly, a case history of using PVD to expedite consolidation is presented.

1. Introduction

Many construction works face a lot of problems when they are carried out on a thick layer of soft clay. Significant consolidation settlement may occur when the soft clay layer is subjected to external loading. Soil improvement is normally required to minimize the post construction settlement. One of the improvement methods is to precompress the soft clay so that most of the consolidation settlement could occur before the construction begins. The post construction settlement in future can be minimized.

The precompression technique is one of the oldest and most common soil improvement methods. The basic principle of this technique is to increase the effective stress in the soft clay either by surcharge or by reducing the pore water pressure of the soil. With the increase in effective stress, the excess pore water in soil is squeezed out, the consolidation process of the soft soil begins. Once the anticipated degree of consolidation settlement has been achieved, the precompression operation can be terminated. However, it may take very long time for the consolidation process to achieve the required degree of consolidation. The process of consolidation is mainly governed by the coefficient of consolidation, Cv, of the soil and by the distance of the drainage path. The coefficient of consolidation is inherent soil property. For large area of filling or reclamation works where the width of the fill is large in comparison with the thickness of soft soil layer, the excess pore water pressure will dissipate mainly in vertical direction. The Cv in a homogeneous compressible soil layer normally will not vary significantly, the consolidation time will be much depended on the thickness of the compressible soil. If Cv is constant, double the thickness of the compressible soil layer will increase the consolidation time by four-fold. It is obvious if the drainage path can be shortened, the consolidation time will be reduced significantly.

Prefabricated vertical drain (PVD) is designed and manufactured for water to flow freely along the drain. To reduce the drainage path in soft clay layer, PVD can be installed in close spacing. The excess pore water pressure in soft soil layer will be able to dissipate in horizontal direction towards the vertical drains and flow freely to the drainage blanket at ground surface or to other permeable layers at deeper depth. The drainage path in the horizontal direction will be much shorter than the vertical direction for thick layer of soft soil and therefore the time for consolidation can be decreased significantly (Figure 1). In addition, the consolidation will lead to the increase of soil strength which allows construction to be carried out faster.

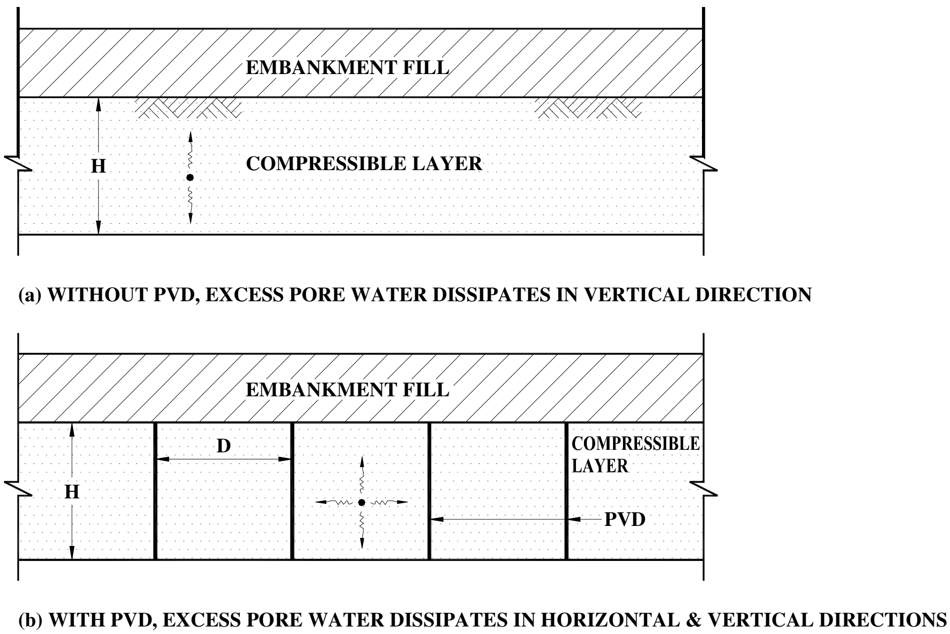
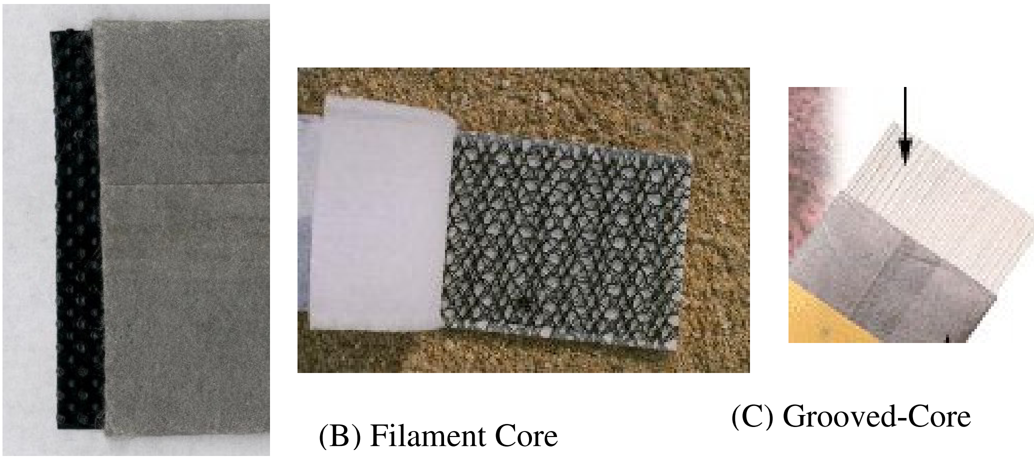


Figure 1. Illustration of shortening of drainage path in thick compressible soil layer

2. Common Types and Characteristics of PVD

PVD is usually band shaped with a plastic core enclosed in a non-woven geotextile filter jacket. There are also some drains that have the core and the filter made into a single unit. Generally there are three types of core namely studded core, grooved core and filament core as shown in Figure 2.

The main purpose of the plastic core is to support the filter jacket and to allow water flow along the drain under lateral soil pressure. It also has the functions of maintaining the configuration and shape of the drain and to provide resistance to longitudinal stretching and buckling. The non-woven geotextile filter jacket separates the flow channel from the surrounding soil and also limit the fines entering into the core to prevent clogging.



(B) Filament Core

(C) Grooved-Core

(A) Studded-Core

Figure 2. Three common types of drain core.

Although there are many types of PVD available on the market today, the dimensions of these drains generally are quite similar. Typical width is around 93mm to 100mm with thickness of about 3mm to 7mm. In the radial drainage analytical model, it is assumed that the drain is a circular cylinder with diameter d. For PVD of band shape with thickness of t and width of b, the equivalent diameter (de) for radial drainage analysis can be expressed by the following equation: (Kjellman 1948, Hansbo 1979):

$$de = \frac{2\,(b + t)}{\pi}$$

This leads to a typical equivalent diameter of PVD in the range of 61mm to 68mm.

3. Consolidation Theories of PVD

The consolidation theories of PVD are basically derived from Terzaghi's one-dimensional consolidation theory (McGown & Hughes, 1981). Rendulic (1935), Carillo (1942), Barron (1944 & 1948) and others extended Terzahgi's consolidation theory to take account of radial flow. Today, the equal vertical strain assumption by Barron is widely used method in the design of vertical drain because of its simpler mathematical equation.

Since Barron's work, many attempts had been carried out to improve the vertical drain theory. Hansbo (1979 & 1981) further developed the equal vertical strain assumption to include the effects of well resistance and smear on drain performance. Figure 3 shows the analytical model for drain with well resistance and smear effects. The degree of consolidation at any depth z with respect to the radial flow only (U_h) is as follows:

$$U_h = 1 - \exp\left[\frac{-8\,T_h}{F(n)}\right]$$

$$T_h = \frac{C_h\, t}{D^2}$$

$$F(n) = \ln\left(\frac{D}{ds}\right) + \frac{k_h}{k_r}\ln\left(\frac{ds}{de}\right) - 0.75 + \pi z\,(2L - z)\,\frac{k_h}{q_w}$$

C_h is the coefficient of consolidation in horizontal direction; t is time of consolidation; k_h and k_r are the coefficients of permeability in horizontal direction of undisturbed soil and disturbed soil respectively; q_w is the well discharged capacity; L is the characteristic length of the drain which equals to half the drain length for fully penetrating drain or entire drain length for partially penetrating drain. D, de, and ds are the diameters of the soil cylinder, equivalent diameter of the PVD and the diameter of smear zone respectively as shown in Figure 3.

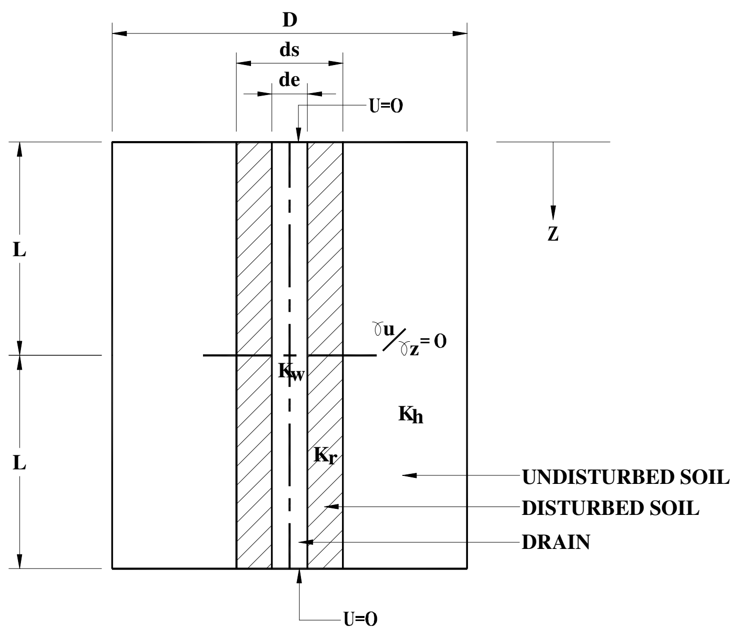


Figure 3. Analytical model of PVD

The average degree of consolidation (U) is the combination of the degrees of consolidation in horizontal direction (U_h) and vertical direction (U_v) (Carillo, 1942).

$$U = 1 - (1 - U_v)\,(1 - U_h)$$

It should be noted that the consolidation theory was developed based on small deformation, linear-elastic behavior of compressible soil and no partial variations of soil properties. A lot of research works had been carried out to overcome these limitations.

4. The Design of PVD

For a site where precompression technique with the use of PVD to expedite the consolidation settlement is an economic solution for subsoil improvement, a proper planning of soil investigation will be necessary. When the subsoil information is available, the theory as mentioned above can be applied.

4.1 Soil investigation and design parameters

The main purpose of the soil investigation is to find out the subsoil condition especially the thickness of the compressible layer. In-situ and laboratory tests are essential as the following geotechnical properties of the compressible soil layer will be required in the design:

a) Stress history and the compressibility properties of the soft soil layer such as preconsolidation pressure, overconsolidation ratio (OCR), compression and recompression indices (Cc and Cr), secondary compression index Cα, initial void ratio (eo) and others for the assessment of settlement.
b) Coefficients of consolidation in horizontal and vertical directions (Ch and Cv) as well as the coefficients of permeability in horizontal and vertical directions (kh and kv) for the assessment of the rate of consolidation.
c) As the installation of PVD will inevitably cause some disturbances to the surrounding soil, it will be desirable to obtain the coefficient of permeability of the disturbed soil which will be required as an input in PVD design.
d) Soil strength of the soft soil for the assessment of the stability of the embankment and surcharge fill.

The commonly adopted approach to determine the consolidation parameters of the soft soil layer in the laboratory is to conduct oedometer test on undisturbed soil samples. However, the test results are usually affected by the sample disturbance. If good quality of undisturbed sample is available, the oedometer test will be able to provide reliable parameters as required in the settlement analysis and PVD design directly and indirectly. The variation of the parameter at different stress level can also be assessed from the laboratory test. Laboratory permeability test is also useful for the determination of the coefficient of permeability. The test can also be conducted on remolded soil sample for the assessment of the reduction of permeability due to the smear effect.

At site, as soil deposit may consist of some macrofabric features such as thin layers or seams of more permeable material, the drainage boundaries will be different from the design assumption. This generally leads to an underestimation of the consolidation rate. Therefore, it is very important for the soil investigation not only to obtain good quality soil samples, but also should try to gather information of any possible existence of thin layers, seams or lenses of more permeable soil in the soft clay layer. In addition to carry out soil boring, Piezocone test (CPT-U) can be a supplementary tool for the investigation of thin layers, lenses and seams of permeable material.

Some consolidation parameters like Ch and kh usually cannot be determined directly from the oedometer test. Although there are suggestions to use vertically trimmed soil sample for oedometer test to determine Ch, some have reported that the results are not reliable (Chu et al., 1997). The more reliable method to obtain the Ch and kh values is to carry out in-situ dissipation tests at designated depths while conducting piezocone test. In-situ permeability test can also be used to determine the field permeability characteristic of the soft layer.

The soil strength can be determined either from laboratory strength tests on soil samples or in-situ vane shear test. The field vane shear test is preferred, as the strength obtained from the test is generally more representatives of the actual site condition.

4.2 Selection of PVD

It is also important to use a suitable type of PVD so that it will not affect the performance of the design drainage system. Generally, the important factors need to be considered in the selection of PVD for a particular site are the discharge capacity, the tensile strength and the geotextile filter characteristic of the drain.

4.2.1 Discharge capacity

The purpose of using PVD is to reduce the drainage path in order to expedite the consolidation process. However, if the discharge capacity of the adopted PVD is less than the amount of water to be released in the compressible soil, well resistance will develop and this will influence the performance of the PVD. To overcome the potential well resistance, it is important to ensure the adopted PVD has large discharge capacity so that the well resistance becomes insignificant.

Studies show that the efficiency of discharging water for PVD installed at a particular site is related to the allowable discharge capacity (q_w) , the maximum discharge length (L) as well as the permeability of the surrounding soil (k_h). A discharge factor (R) in terms of q_w defined as follow is usually used for the assessment of the required discharge capacity.

$$R = \frac{q_w}{k_h L^2}$$

Based on the study by Mesri and Lo (1991), if R is more than 5, the well resistance will be insignificant. Therefore the minimum required discharge capacity for a PVD, $q_{w(min)}$ is equal to $5k_hL^2$. For most of the soft clay deposit, the typical coefficient of permeability is less than $1x10^{-9}$ m/s and the discharge length is generally less than 30m, the required q_w will be less than 150 m3/yr. It should be highlighted that the minimum q_w is required only at the beginning of the consolidation. The permeability of the soft clay layer will be decreased during the consolidation process which means that the required q_w will be smaller.

The study by Mesri and Lo also presented the field mobilized discharge capacity and compared to the required discharge capacity for 4 major embankment construction sites. It appears that the minimum required discharge capacity of 100 m3/yr will be sufficient for most of the cases. This is quite similar to the recommendation by Holtz et al. (1991) that the minimum q_w should be about 100 to 150 m^3/yr under a confining pressure of

300 to 500 kPa. Bergado et al. (1996) also mentioned that the selected PVD should have q_w of at least 100 m^3/yr measured under gradient of one while confined to maximum in-situ effective lateral pressure. For most of the PVD available on the market today, the discharge capacity generally should not be a problem to meet the requirement.

4.2.2 Tensile strength

The required tensile strength for PVD is to ensure that the PVD will not be damaged during the installation. In general, the required longitudinal strain at failure should not exceed 10%. This is to limit the deformation of PVD which may cause undesired decrease in dimension. Tensile strength of 1 kN at either dry or wet conditions is usually adopted in practice. According to the field measurement on the tensile force on PVD by Karunaratne et al. (2003), a tension of about 1 kN was measured near the shoe after the commencement of the withdrawal of mandrel. It seems that the criteria of 1 kN is quite a reasonable value.

4.2.3 Geotextile filter

The geotextile filter separates the flow channel from the surrounding soil. It also limits the fines from entering into the core to prevent clogging. Therefore the selected PVD shall have a filter with Apparent Opening Size (AOS) small enough to retain fines from entering the core. However, in contrast to the requirement of small AOS, the geotextile filter should have sufficient large enough AOS so that the filter is more permeable than the surround soil.

The AOS or Equivalent Opening Size (EOS) is an indication of the size of the fabric pore opening of filter. The sizes of pore opening for a filter normally fall within a certain range. The definition of AOS or EOS is slightly different by different organizations or institutions. In general, it is defined as the size that is larger than 90% or 95% of the fabric pore denoted as O_{90} or O_{95} (i.e. O_{95} is adopted in ASTM, USA while O_{90} is commonly used in Netherlands).

The retention criteria

There are many soil retention formulae available for the design of non-woven geotextile in clayey soil with more than 50% soil particles passing a No. 200 sieve, i.e. diameter of 0.075mm. The retaining ability of the geotextile filter is quite complicated. In practice, O_{95} of 0.075mm is generally adopted in the preliminary design.

The permeability criteria

To prevent slowing down the flow from soil into the PVD, the permeability of the geotextile filter shall be at least or larger than the permeability of the surrounding soil. The generally adopted permeability criteria depend on the nature of the project:

For critical application and/or severe condition:

$$k_{geotextile} \geq 10\ k_{soil}$$

For less critical and less severe condition:

$$k_{geotextile} \geq k_{soil}$$

For most of the PVD, the permeability of the geotextile filter jacket is usually more than the requirement.

The clogging resistance criteria
These criteria are to prevent soil particles trapped in the filter and cause clogging. For non-woven geotextile, the criteria are as follows (Holtz et al. 1991):

Porosity of geotextile ≥ 30%
$O_{95} \geq 3\ d_{15}$
$O_{15} \geq 2$ to $3\ d_{15}$

5. Smear Effect

The disturbance due to the installation of PVD is similar to that caused by the driven displacement pile. As the installation of PVD is usually carried out by a statically or sometime vibratory driven mandrel, the degree of disturbance to the surrounding soil is related to the size and shape of the mandrel as well as to the size of the detachable shoe or anchor. The disturbed zone having diameter of ds around the drain is called smear zone. Due to the disturbance, the permeability and the preconsolidation pressure of the soil are reduced, and the compressibility increases.

The decrease in horizontal permeability is most significant. For most of the soft clay, silt and organic soil, the ratios of kh/kv are generally less than 3. For marine clay with homogeneous deposit environment, the ratio of kh/kv is around 1 to 1.5; For lacustrine clay, varved clay and clays with discontinuous lenses and layers of more permeable materials, the ratios of kh/kv are in the range of 2 to 5 (Mesri & Lo, 1991). The laboratory test results by Indraratna and Redana (1998) revealed that there will be a significant reduction in the horizontal permeability in smear zone but the vertical permeability remains unchanged. For design purpose, the permeability of the disturbed soil can be assumed equal to the kv (Hansbo, 1987).

The extent of the smear zone, ds, is difficult to estimate. However, it appears that it could be related to the sensitivity of the subsoil as shown in Figure 4. For soft clay with sensitivity less than 8, the values of ds/de as shown in Figure 4 are mostly in the range of 1.5 to 3. This is quite similar to the values as reported by most of the literatures (Hansbo 1979). For design purpose, the value of 2 is usually adopted. It should be noted that the dw should be the equivalent diameter of the mandrel instead of the equivalent diameter of the PVD.

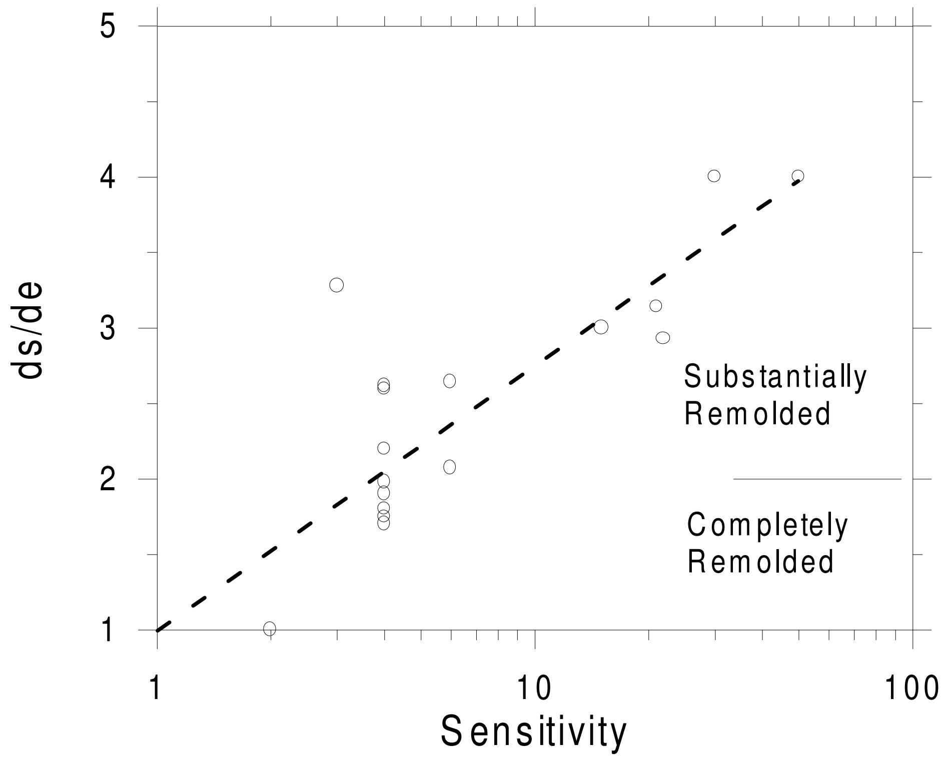


Figure 4. Relationship between smear zone and sensitivity of soil (Mesri & Lo, 1991)

6. Case History

6.1 General description of the project

This project was a reclamation work for a development on a piece of mangrove swamp land in the coastal area at Pulau Indah, Klang. The site is approximately rectangular shape with about 200m wide and 650m long. The average ground level within the reclamation area was about +5m CD. At high tide condition, almost the entire site is submerged.

The proposed development required to have a platform with designed surface level of +7.2m CD. Average of 2.2m fill will be required. As the subsoil at site mainly consists of very soft and highly compressible silty clay, excessive post construction settlement was expected. Precompression technique with PVD to expedite the settlement was found to be a feasible and economical method to treat the subsoil within the given period.

6.2 Subsoil condition

The subsoil at site mainly consists of a layer of soft clay of about 10m thick on the land side and getting thicker towards the seaside to about 25m thick. Underlying are loose to medium dense silty sand and medium stiff silty clay layers. Very dense or hard soil layer could only be found at 40m below the ground surface.

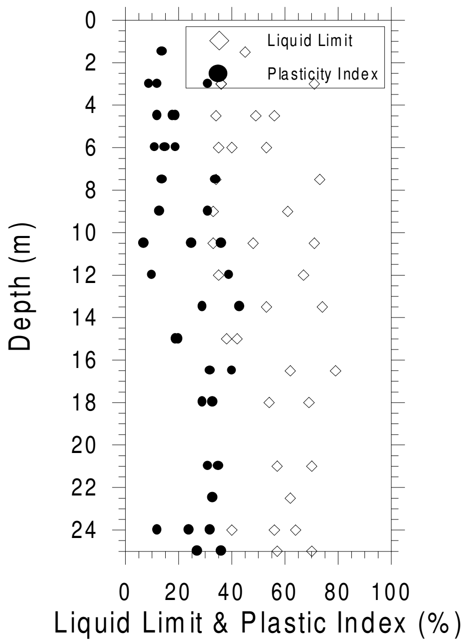


Figure 5. Soil physical properties

The Liquid Limits (LL) of the soft clay are in the range of 40% to 80% while the Plasticity Indices (PI) are about 10% to 30% in general. Figure 5 shows the LL and PI of the soft clay layer.

The undrained shear strength (Su) of the soft clay was obtained from field vane shear test and also from laboratory unconsolidation undrained triaxial compression test on the undisturbed soil samples. A 76mm (3") diameter piston sampler was used to obtain undisturbed soil samples. Apparently the undrained shear strengths as obtained form the field vane shear tests are higher than the results from laboratory triaxial tests. This could be due to the disturbance of the soil samples. Figure 6 shows the Su of the clayey soil at various depths. The Sensitivity of the clay layer is about 2 to 4.

The compressibility properties of the soft clay are obtained from laboratory oedometer tests. The void ratio (e0) of the soft clay is about 1 to 2.5. Compression Ratio defined as Cc/(1+e0) is at about 0.15 to 0.3 as shown in Figure 7. The coefficient of consolidation (Cv) as shown in Figure 8 varied quite significantly but generally within 1 to 3 m^2/yr. Soil samples with higher sand content show much higher Cv values. The preconsolidation pressures (Figure 8) obtained from the test show that the soft clay can be treated as normally consolidated clay in design.

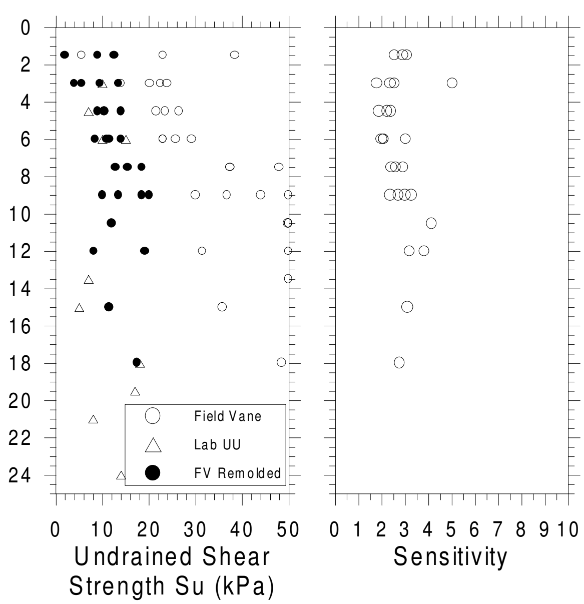


Figure 6. Undrained shear strength and Sensitivity

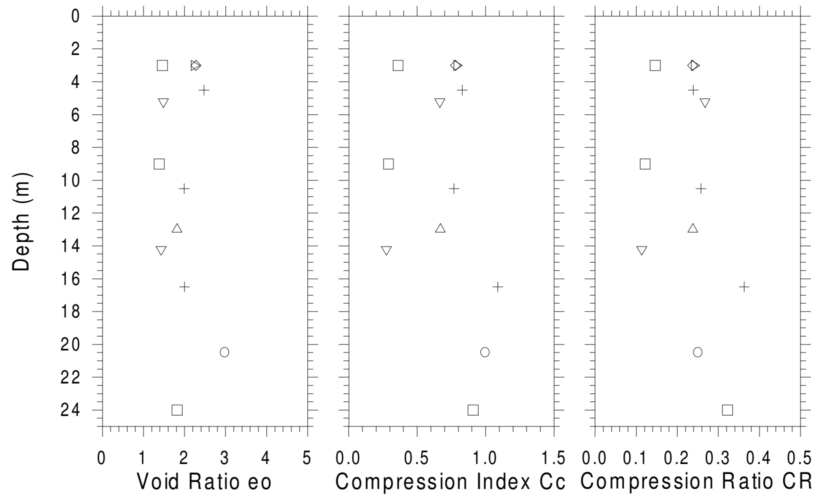


Figure 7. The Compressibility properties of soft clay.

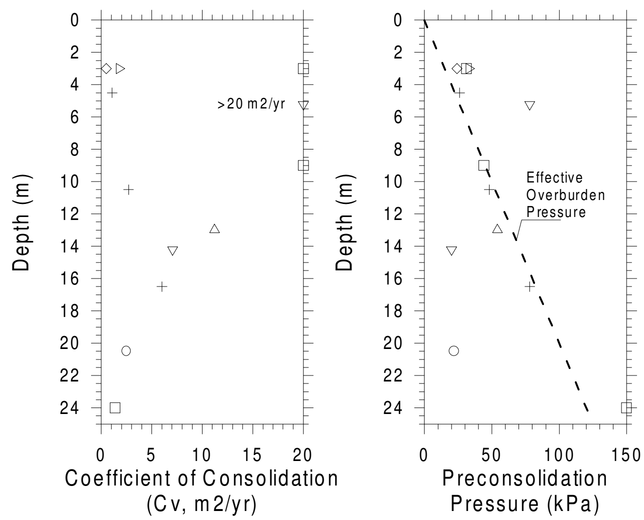


Figure 8. Coefficients of consolidation and Preconsolidation Pressures.

6.3 Potential problems

There are two potential problems for the reclamation work carried out at this site. Stability of the platform could be the main problem during the reclamation. After the reclamation, the long term settlement could be too excessive. Stability analysis was carried out and it was found that with a gentle slope and proper control of filling rate, the stability of the reclaimed platform will not be a major concern.

The long term settlement was assessed using Terzaghi's one dimensional consolidation theory. With the assumptions that the soft clay is normally consolidated and the average Compression Ratio (CR) of about 0.25, the estimated long term settlement due to the 2.2m fill was about 1m to 1.6m. It may take 11 years to 65 years to complete 90% of the expected settlement for 10m and 25 m thick soft clay respectively assuming two ways drainage and Cv of 2 m^2/yr.

To overcome the excessive long term settlement problem, it was decided to preload the subsoil so that the anticipated settlement can be eliminated or significantly reduced.

6.4 Design of PVD

The preloading method is the oldest and very effective soil treatment method. However, for a thick compressible soil layer, it may require very long time to eliminate or reduce the settlement due to the low permeability characteristic of the soft clay. PVD is generally used to shorten the drainage path and to accelerate the consolidation process. In the design of preloading with PVD, the targeted settlement to be eliminated should be the estimated settlement due to the effective permanent loading. For this project, as the estimated settlement was about 1.6m for the worst case, the permanent effective pressure was about 52.4 kPa assuming the unit weight of the fill is 18 kN/m3 and the ground water level is at ground surface.

The spacing of PVD and the surcharge height are the two variables to be determined in the design. Generally the closer the spacing of PVD, the shorter the required resting period. Alternatively, higher surcharge level will also shorter the required resting period. However, too high surcharge level is not preferred as this may cause stability problem during the construction period. For this project, the adopted PVD spacing was 1m in square grid and the surcharge level was about 10m CD. The targeted resting period was 4 months.

The ALIDRAIN type SSXK 9 was used in this project. The specifications of the product and the test results are presented in the following Table.

Table 1. Product Specifications and test results

	Specifications	Test Results
<u>Dimension</u>		
Width	100 ±3 mm	99 – 102 mm
Thickness	5 mm	5.7 – 6.3 mm
<u>Discharge Capacity</u>		
Straight (at 240kPa)	1890 m^3/yr	1920 – 2012 m^3/yr
Kinked (at 240 kPa)	1260 m^3/yr	1458 – 1589 m^3/yr
Opening Size O_{95}	<90 µm	<75 µm
<u>Tensile properties (entire drain)</u>		
Tensile strength	2500 N	2630 – 2703 N
Elongation at break	>20%	31 – 37 %
Elongation at 1 kN	< 8%	2.8 – 5.7 %
<u>Filter properties</u>		
Tensile strength	9 kN/m	9.5 – 10.9 kN/m
Elongation at break	<40%	31- 46%
Coefficient of permeability	15 x 10^{-4} m/s	15.6 x 10^{-4} – 18 x 10^{-4} m/s
<u>Core properties</u>		
Tensile strength	1000 N	1047 – 1201 N
Elongation at break	20%	16 - 21 %

6.5 The settlement monitoring results

Due to the natural variability of the subsoil properties as well as the limitations of analytical theory, monitoring of the subsoil behavior during and after the reclamation work is required. The monitoring results can lead to a better understanding of the actual behavior of the in-situ subsoil and more importantly, to verify the design where the subsoil has achieved the targeted degree of settlement.

The reclamation work commenced in June 2003 with the placement of the initial sand fill. After the installation of PVD, the filling work continued for another three to four month times to reach to the design surcharge level. The rod settlement plates were installed prior to the backfill. Monitoring was carried out during and after the reclamation work. Figure 9 shows the settlement monitoring results.

The degree of consolidation of the subsoil can be assessed based on the settlement monitoring results. There are two commonly adopted methods namely Asaoka method (1978) and hyperbolic method for the assessment of the final settlement (S_f). The Asaoka method is relatively more attractive because it is easy to use. When the final settlement is known, the average degree of consolidation at any time t (U_t) with the monitored settlement of S_t is defined as:

$$U_t = S_t / S_f$$

Figure 10 shows the estimated final settlements for settlement plates SP1 and SP5 are about 1950mm and 2400mm respectively. The average degrees of consolidation are about 93% and 95%.

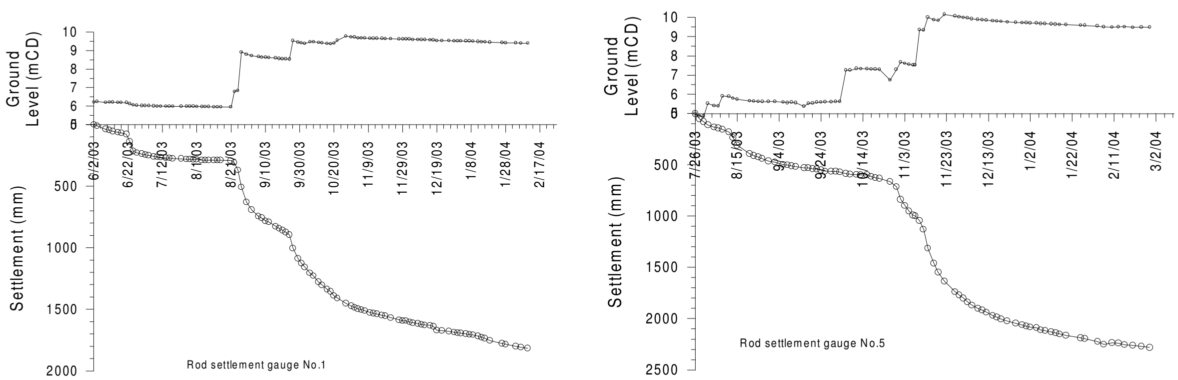


Figure 9. The settlement monitoring results for SP1 (left) and SP5 (right)

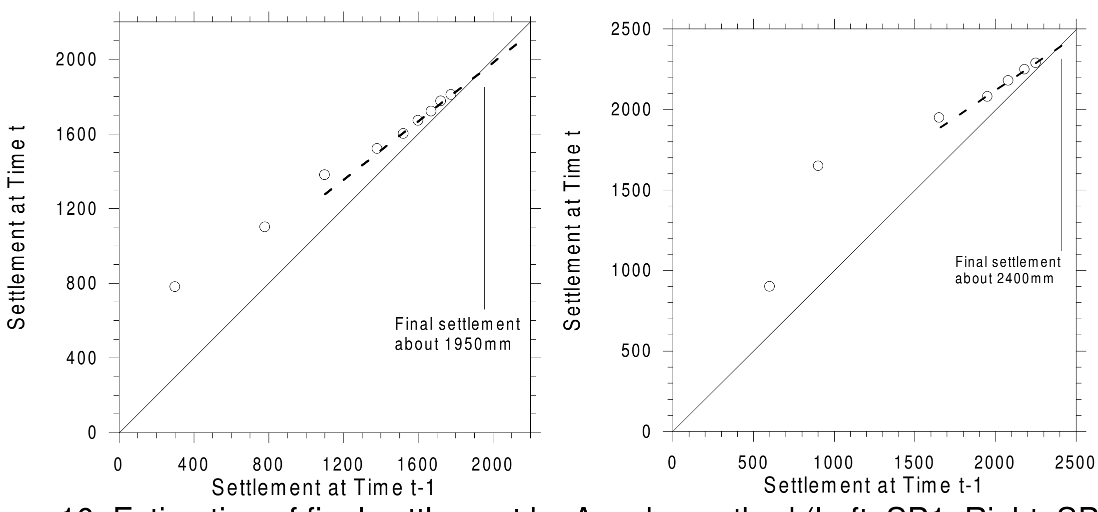


Figure 10. Estimation of final settlement by Asaoka method (Left: SP1, Right: SP5).

7 Conclusions

Use of PVD to shorten the drainage path is an effective measure to expedite the consolidation process of thick layer of soft clay. Generally the discharge capacity of the PVD available on the market will be large enough to minimize the well resistance. The main factor that may affect the performance of the PVD is the smear effect due to the disturbance during the installation. Due to the inherent variation of the soil properties and the limitation of design theory, monitoring program is always required during and after the earthwork.

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