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Quality management of prefabricated vertical drain materials in mega land reclamation projects: A case study

Myint Win Bo[a], Arul Arulrajah[b], Suksun Horpibulsuk[b,c,*], Melvyn Leong[d]

[a]*DST Consulting Engineers Inc., Thunder Bay, Canada*
[b]*Swinburne University of Technology, Melbourne, Australia*
[c]*School of Civil Engineering, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon-Ratchasima 30000, Thailand*
[d]*Geofrontiers Group Pty Ltd., Melbourne, Australia*

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Abstract

The quality management of Prefabricated Vertical Drain (PVD) material installation in ground improvement works in land reclamation projects is a critical task for designers, contractors and clients alike. Only if a good quality management system is established, can the expected performance of the PVD improvement works in the field be ensured. A case study of quality management of PVD materials in the mega Changi East land reclamation Project in the Republic of Singapore is presented in this technical report. The quality management of PVD works consisted of several processes, starting from selection of the type of PVD, properties of the PVD materials and ultimate performance verification in the field. This paper describes selection of PVDs against the comprehensive specification adopted in this project. The paper also describes the selection of the PVD installation rig and accessories based on the in-situ ground conditions. Test results from quality control test laboratories such as tension, permeability and discharge capacity are also presented and discussed. This paper seeks to set a benchmark for material quality management of PVD works in large-scale PVD ground improvement projects.

Keywords: Geosynthetics; Prefabricated vertical drains; Ground improvement; Quality control; Discharge capacity; Land reclamation

1. Introduction

PVDs are increasingly being used as the preferred ground improvement option in mega land reclamation projects on soft soil or ultra-soft soil deposits, particularly in Asia (Arulrajah et al., 2009; Bo et al., 1999, 2011, 2014; Bergado et al., 2003; Chu et al., 2006, 2009). This is because they are economical, simple to install and readily availability. PVDs are particularly suitable for projects that have long construction durations, since this ensures sufficient time for the required degree of consolidation to be attained. PVDs are often used in locations with thick deposits of soft soil in marine or estuarial environments. PVDs are implemented with a combination of surcharge preloading (Arulrajah et al. 2004a, 2004b; Bo et al., 2012; Indraratna et al., 2005; Wu et al., 2015) or vacuum preloading (Rujikiatkamjorn et al., 2007) to induce the occurrence of consolidation settlement during the construction period and to minimize post construction settlement.

The Changi East land reclamation project in the Republic of Singapore, undertaken from 1992 to 2005, was a mega land

*Corresponding author at: School of Civil Engineering, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon-Ratchasima 30000, Thailand.

E-mail addresses: mwinbo@dstgroup.com (M.W. Bo), aarulrajah@swin.edu.au (A. Arulrajah), suksun@g.sut.ac.th (S. Horpibulsuk), geofrontierslimited@gmail.com (M. Leong).

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Table 1
Various Specifications called by varios clients.

Description	Unit	Standard	Nether land		Singapore	Thailand	Hong Kong	Malaysia	Taiwan	Australia	Finland	Greece
			Stable layer less than 10 m thick	Unstable layer larger than 10 m depth								
With	mm	ASTM	100	100	100	W/T 50:1		95	100	100	100	100
Thickness	mm	D1777			3–4			3	3–6	> 3		> 3
Tensile Strength (Dry)	kN	ASTM	> 0.5	> 0.5	> 1 (10%)		> 0.5		> 2		> 1	> 1
(Wet)	kN	D4595	> 0.5	> 0.5	> 1 (10%)				> 2		> 1	> 1
Elongation	%		2–10 (0.5 kN)	2–10 (0.5 kN)	< 30 (1 kN)				< 20 (Yield)		15–30	
Discharge capacity	$m^3/s \times 10^{-6}$	ASTM	> 10	> 50	> 25	> 16	> 5	> 6.3	> 10	> 100	> 10	> 10
Straight		D4716	350 kPa 30 days	350 kPa 30 days $i=1$	351 kPa 28 days	200 kPa 7 days $i=1$	200 kPa	400 kPa $i=1$	300 kPa $i=1$	300 kPa		100 kPa
Discharge capacity	$m^3/s \times 10^{-6}$		> 7.5	> 32.5	> 10			> 6.3				
Floded			350 kPa	350 kPa 30 days				400 kPa 40 m				
Crushing strength	kN/m^2							500				
Equivalent diameter	mm						50		65			
free surface filter	mm^2/m						150,000					
Elongation	%				< 30 (3 kN)				< 40		> 15	
Tear strength	N	D4533				100		> 300	> 250	> 380		
Grab strength	N	D4632				> 350						
Puncture strength	kN	D4833				> 200						
Bursting strength	kPa	D3785				> 900						
Poresize O_{95}	mm	D4751	< 160	< 80	< 75	< 90	< 120	< 75			< 90	
Permeability	mm/s	D4491			> 0.05		> 0.1	> 0.01	> 0.1	> 0.17		> 0.5
Permittivity	s^{-1}		> 0.005	> 0.005							> 0.005	

reclamation and ground improvement project. Approximately 140 million linear meters of PVD were installed in this project in an area totaling approximately 1000 ha. Due to the large quantity of drains which needed to be installed, it was not practical to solely rely on one specific type of PVD supplied from a single source and installed by a single contractor. As such, various types of PVD and several installation contractors with different types of installation rigs were deployed in the project. A rigorous quality management system was adopted in the project to ensure the performance verification of PVDs in the field. The quality management system implemented included controlling the quality of PVDs at every stage of the project inclusive of commencement, selection of PVD materials and ending with the installation of PVDs.

The stages of the adopted quality control process in PVD works in this project were as follows: (i) selection of material against specification; (ii) planning and deployment of suitable type of vertical drain rig, including special type of rigs required for difficult ground conditions; (iii) selection and quality control of accessories such as mandrels and anchors; (iv) quality control of PVD material; (v) quality control of PVD installation. This process of quality management for all these stages of PVD implementation in Changi East land reclamation project is described in this paper.

For the quality management of PVD materials, three types of laboratory testing organizations were adopted: an on-site laboratory, a research laboratory and a third party laboratory. The on-site laboratory was used to carry out two types of test such as discharge capacity and tensile strength tests since these are essential parameters for vertical drain performance and the strength required to withstand penetration force. Discharge capacity is a critical parameter for vertical drain performance (Bo, 2004; Bo et al., 2007; Sharma and Xiao, 2000; Sprague, 1995; Tripathi and Nagesha, 2010) and the tests to determine this can be undertaken in the laboratory (Bergado et al., 1996) or carried out by in-situ testing or instrumentation in the field

Table 2
Specification for prefabricated band-shaped plastic vertical drain (Requirement vs. supplied materials).

Property		Unit	Specified requirements	CX 1000	Colbond Holland	MD 7007 Korea	MD 7007 Malaysia	MD 7007 FD 767	Flexi
Material	Core			Continues plastic drain core wrapped in non-woven geotextile material	Polyester	Corrugated	Corrugated	Corrugated	Corrugated
					Filament Polyester	38 groves PP	40 groves PP	37 groves PP	39 groves PP
	Filter				Non-woven	non-woven	non-woven	non-woven	non-woven
Dimension of drain	Width	mm	100 ± 2		100	103	103		100 ± 2
	Thickness	mm	3 to 4		5	3.1	3.4		3.5 ± 0.2
Darcy Permeability		m/s	$> 5 \times 10^{-4}$		15×10^{-4}	1×10^{-4}	1×10^{-4}	1.02×10^{-4}*	1×10^{-4}
Discharge capacity of drain		m^3/s	$> 25 \times 10^{-6}$	At 350 kN/m soil pressure after 4 weeks	90	95	100	69*	52
Discharge capacity of drain under deformation		m^3/s	$> 10 \times 10^{-6}$	At 25 % relative compreesion	80	71	77	45*	45
Soil retention capacity		microns	AOS 095 < 75		< 75	73	73	40*	75
Tensile strength of entire drain	Dry	kg/10 cm width	> 100	At elongation minimum 2% maximum 10%	210	220	250	147*	294*
	Wet	kg/10 cm width	> 100	At elongation minimum 2% maximum 10%	232*	212*	275*	167*	310*
Tensile strength of filter	Dry	kg/cm	> 3	Test at 1% strain/min after	11	40.8	40.8	89*	80*
	Wet	kg/cm	> 3	saturated in H_2O at 10 °C for 48 h	11*	49.7*	68.4	97*	95*
Elongation of entire drain	Dry	%	< 10	At 100 kg/10 cm width	6*	3% at 50 kg/cm	2*	4*	
	Wet	%	< 10	At 3 kg/cm	2*	4*	4*	1.4*	2*

*Tested at third party laboratory.

(Arulrajah et al., 2005, 2006, 2013; Bo, 2004; Tripathi and Nagesha, 2010).

By monitoring the index test results obtained from every 20,000 linear meters of vertical drains, the quality consistency of material being used is maintained. Any deviation of quality of material from the specifications resulted in rejection on site by the client manager. The research laboratory on the other hand was utilized to determine the in-situ actual performance of the PVD by simulating field conditions in the laboratory and undertaking specialized tests to determine the factors affecting parameters. The measured parameters from the third party laboratory were used to determine the acceptance of delivery of material on site. The frequency of the PVD quality assurance test was one complete suite of tests per million meters length of drains.

2. Selection of material against specification

The popularity of PVD in ground improvement projects in the last two decades has given rise to a phenomenal increase in the variety of PVDs produced by various geosynthetic manufacturers. PVDs now come in various shapes and sizes. The PVD core and filter design, including the type of material used varies from one type and one manufacturer to another. The performance of PVDs depends primarily on the site conditions and surrounding soil properties. The quality of PVDs deteriorates with time and it is thus necessary to have a reliable specification, which accounts for all these factors as well as any specific project design requirements. The properties of PVD are important and might change after installation and during the consolidation process. As such, specification must be adopted for specific conditions, which will reflect the actual in-situ condition.

Due to the differences in site conditions, various combinations of specifications were specified. Table 1 shows a comparison of the specifications for various projects around the world. Due to very deep installation of PVD greater than 40 m, several requirements of PVD were specified. These requirements included higher tensile strength in combination with smaller apparent opening size and higher discharge capacity under confining pressures greater than 350 kPa.

Table 2 shows a comparison of the specifications for PVDs for the Changi East Land Reclamation project with the manufacturers' specification of selected materials. As evident in the table, all the selected materials met the specification requirements.

3. Planning and deployment of vertical drain rigs

The selection of PVD installation rigs is essential for implementation in PVD projects and is based predominantly on the following factors:

(i) Bearing capacity of PVD installation platform
(ii) Depth of installation
(iii) Type of soil
(iv) Production capacity of rig.

The size and weight of the rig should be suitably matched with the bearing capacity of the PVD installation platform. In this project, the installation platform is an hydraulically fill granular sand with a minimum thickness of 6 m. The mobilization of an overweight rig would have led to the instability of the equipment. On the other hand, a low capacity rig would not have provided sufficient penetration capacity or reaction against penetration resistance.

The depth of installation and soil types are important factors. Determining the most suitable height of rigs depends on the depth of installation. The capacity and type of rig also needs to be selected based on the type of in-situ soil. The productivity of the rig is similarly important. For this project, installation rigs with a minimum capacity of 8000 m/day were required to cope with the project schedule.

Table 3 shows types and details of rigs mobilized in the project. Table 4 shows the specification for high power installation rigs mobilized for difficult conditions.

3.1. Managing difficulties in installation

During the course of the installation of PVDs, installation difficulties are sometimes encountered. Difficulties are often encountered in hard ground and very soft ground conditions. The types of difficulty and suitable trouble shooting techniques adopted in the Changi East Land Reclamation project are described in this section. Fig. 1 shows the various types of PVD installation equipment used for penetrating difficult ground. Table 5 shows the various specialized rigs mobilized for trouble shooting at site.

3.1.1. Top hard crust at seabed

Sometimes recent alluvial deposits such as sand were found overlying a marine clay deposit. The density of such a deposit varies and is dependent upon the depositional environment at the old estuary. In such cases, difficulty in penetrating through dense sand deposit just below the sand fill was encountered. This condition was overcome by loosening the dense granular material using a penetration rig with a high capacity water jetting system.

There were also cases where very stiff to hard clay was encountered at the seabed due to desiccation of the upper part of the marine deposit during the previous fluctuations of the sea level. This situation was overcome by using pre-punching equipment or auguring equipment to penetrate the hard crust encountered at shallow depths.

3.1.2. Intermediate hard crust at intermediate depth

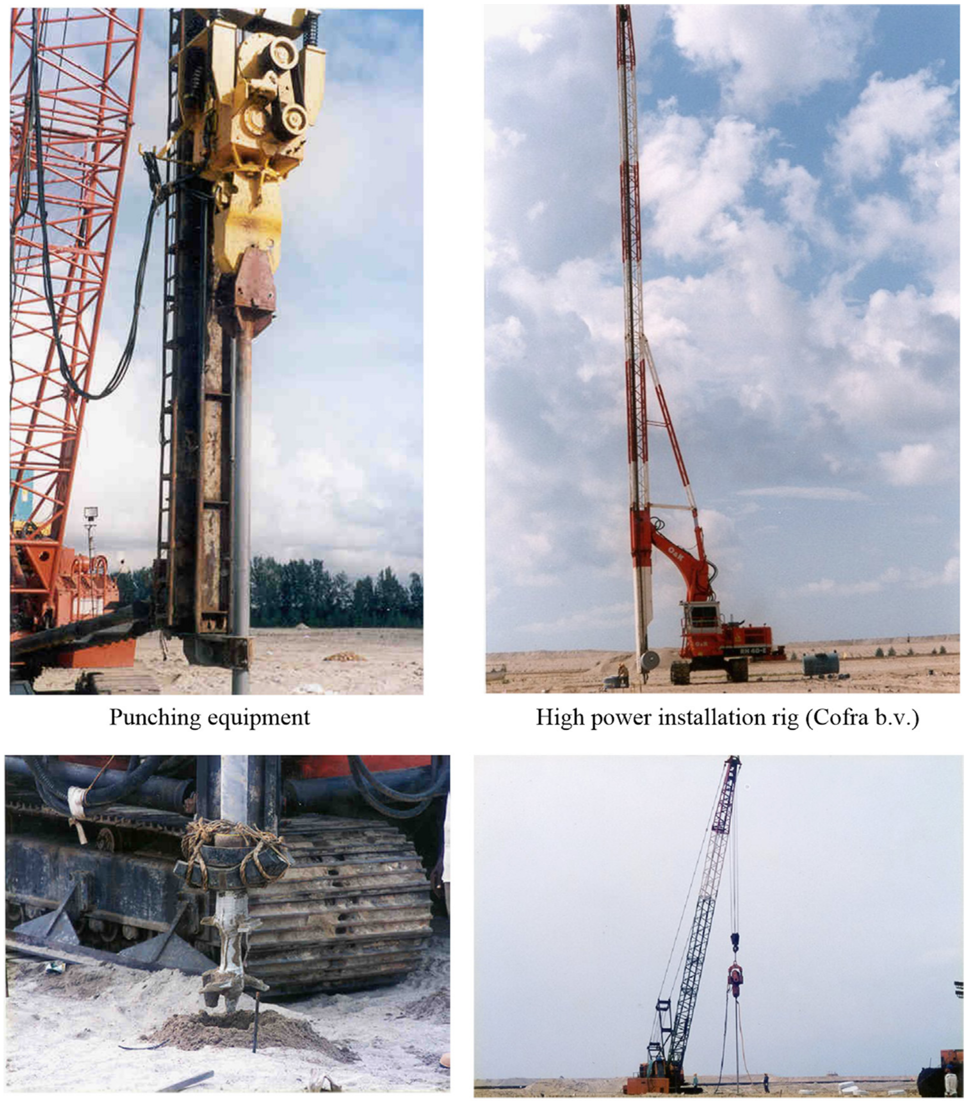
During the geological history of deposition, some non-conformity or change in type of deposition could have occurred due to a change in the environment. For example, the desiccation of a young deposit due to the receding sea level before the next layer of deposition of younger marine deposits at Changi. Another example is the deposition of an alluvial deposit during the paused period of marine formation deposition. In such cases, an intermediate hard layer of clay

Table 4
Specification of high power installation rig.

Displacement	min	3140	cc/revolution
Operating pressure	max	350	bar
Operating speed	max	280	rpm
Flow	max	700	l/min
Torque		35,000	N/m
Power		275	kW
Weight		200	kg

Table 3
Types of vertical drain installation rigs used at the Changi East Land Reclamation project.

Description	Type of base machine	Weight of base machine: (ton)	Penetration power (ton)	Height of rig (m)	Maximum penetration depth (m)	Mechanism of penetration	Maximum production/ day (m/14 h)
Cofra	O & Kexcavator RH30, RH40	70–110	20–30	36–55.5	50.5	Hydraulic motor, Multi pulley system	33 400
Econ	O & KExcavator RH30, RH40 (01)Hitachi Excavator EX1100	70–120	20–30	36–56.1	51.5	Hydraulic motor, Multi pulley system	27 500
Yuyang	Samsung CX800 crane, Daewoosolar 450IIIExcavator, Zeppelin crane, P & H Crane, Komaso excavator IHI crane	45–100	25–30	43–55.8	53	Hydraulic motor, Multi pulley system,Driven chain and cable system	15 300
Chosuk	Daewoo solar 450 Excavator	45	25	56	51	Hydraulic cylinder, multi pulley system	17 900
Daeyang	Daewoosolar 450III Excavator	33–55	20–34	42–56	52	Hydraulic motor Push in roller and clamp system	15 200
B+B	Excavator	–	–	31–47	29–45	Hydraulic sprocket and chain	19 200
B+B	Excavator	–	–	43–50	41–48	Vibro push-in	8 600



Punching equipment — High power installation rig (Cofra b.v.) — Auger drill — Vibrating puncher

Fig. 1. Various types of PVD installation equipment for penetrating difficult ground.

Table 5
Specialized rigs mobilized for trouble shooting.

Type of rigs	Purpose
Vibratory rig	To penetrate stiff layer at depth
Rig with water jetting	To penetrate through dense granular soil at intermediate depth
Prepunching rig	To punch through dense or dessicated stiff layer at seabed.
Auger rig	To auger through dense and stiff layer at shallow depth
Rig with water balancing system	To prevent soil ingression into the mandrel during installation in very soft soil
High power slow speed Rig	To penetrate through dense layer at deeper depth

or dense layer of sand might be encountered. The degree of hardness of the desiccated clay and the extent of desiccation are dependent upon the duration and thickness of the cohesive deposits exposed to the atmosphere. The problem of penetration in an intermediate hard layer was solved by using the same type of equipment described earlier or alternatively by utilizing a vertical drain rig with a vibratory system.

3.1.3. Hard or dense layer at deep seated formation

On rare occasions, a thin layer of hard clay or dense sand was encountered at a deep-seated depth above soft soil deposits of

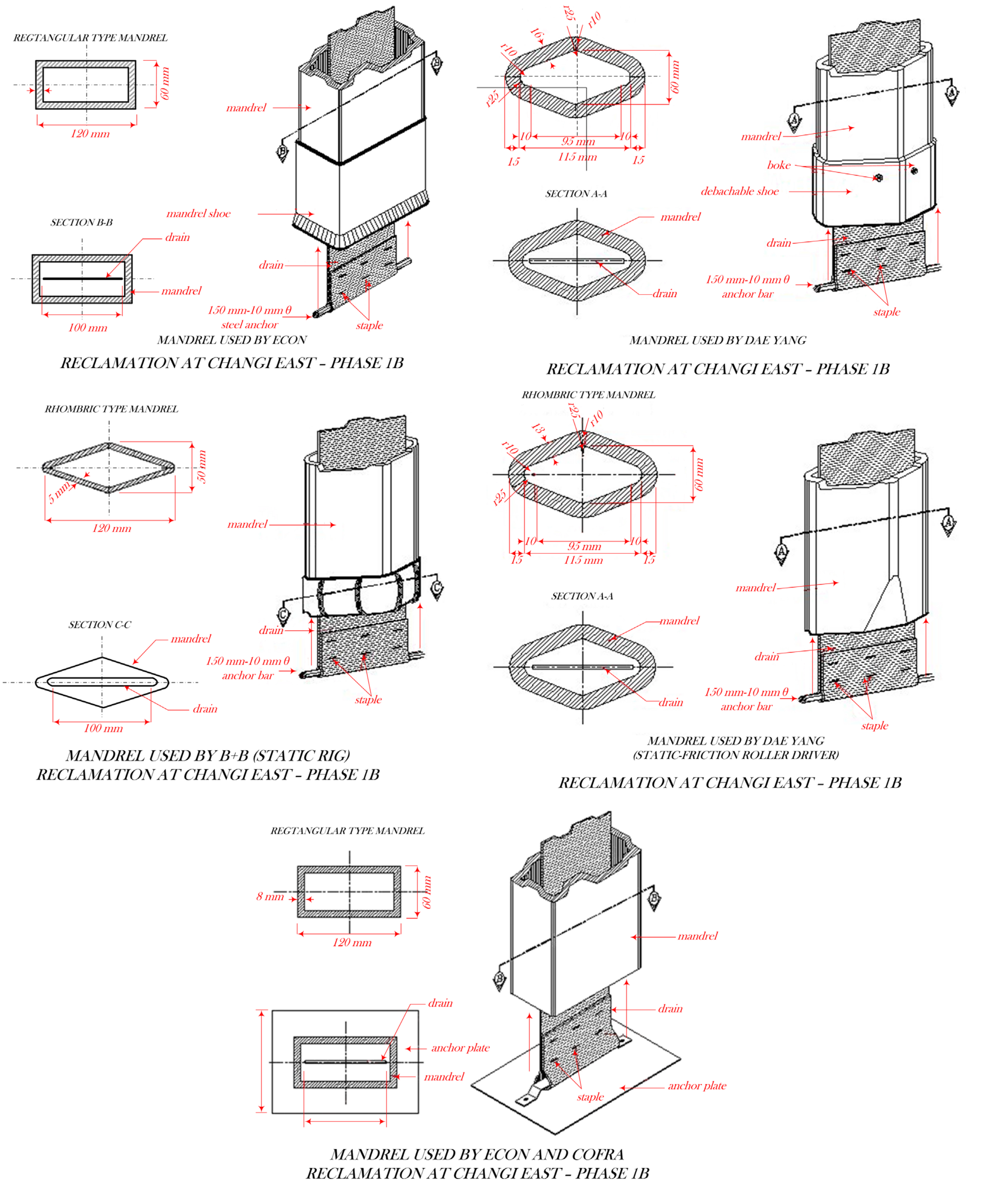


Fig. 2. Mandrels and anchors of various shapes used in the project.

significant thicknesses, which would thus require PVD treatment. In such situations, using the equipment described earlier would have been impossible and would have consumed a lot of time and cost. In this project, high-powered low speed PVD installation rigs were fabricated to be punched through this deep seated hard layer and to treat the underlying soft marine clay. The equipment used was able to penetrate a hard layer, having a Standard Penetration Test blow count of 30 at a depth of 30–40 m from the installation platform level. The specification of this special equipment is shown in Table 4.

3.1.4. Installation through ultra-soft clay

Another major problem encountered in installation of PVDs was the necessity for installation through ultra-soft clay at various locations. Problems encountered in this situation were extrusion of mud along the annulus of the penetration hole, which could contaminate the drainage layer or the intrusion of mud into the mandrel leading to unsuccessful anchoring of the vertical drain. Both problems were reduced by introducing a water balancing system to counter balance the excess pore pressure encountered in the formation. In order to counter balance the excess pore pressure encountered during installation, a water head equivalent to excess pore pressure was applied within the mandrel. A smaller dimension mandrel with a smaller anchor was also suitable in this situation.

4. Selection and quality control of mandrels and anchors

There are various types of mandrels: rectangular, square, rhombic and circular. However, circular and square mandrels are now rarely used. In order to minimize the disturbance of soil to be improved, smaller size mandrels are normally preferred. The rhombic type mandrel has reduced dimensions, leading to lesser disturbance. This was suitable for shallow depth penetration in soft to very soft soil because smaller dimension mandrels had inadequate penetrability in deep depth penetration, leading to non-verticality during installation. Apart from the selection of mandrel, regular checking and maintenance of mandrels was required.

Due to the installation through the highly abrasive granular fill, mandrels were frequently worn out. A tilted tip of mandrel leads to deviation in verticality. As such, the condition and dimension of the mandrel were regularly checked. A maintenance schedule for the replacement of the tip of the mandrel as well as the entire length of mandrel based on the total penetration length of PVD was necessary.

In addition to the mandrel, another important accessory is the anchor. Anchors should be strong enough to anchor the drain and to prevent the ingress of soil into the mandrel. The two main types of anchors used in this project were steel bars and flexible metal plates. There are pros and cons in using steel bars and the flexible metal plates. The steel bar minimizes disturbance due to its smaller dimension and is suitable for smaller mandrels with tapered shoe in which a steel bar can be fitted. If the steel bar is used with the larger mandrels, a water balancing system will be required. Although the flexible metal plate creates more disturbances, it is suited for large dimension mandrels and may not require a water balancing system. The formation of smear zone varies depending upon the size and shape of selected mandrels and anchors. The brief discussion on the smear effect is described in subsequent paragraph. Fig. 2 shows the types of mandrels and anchors used in this project.

4.1. Smear effect

Several researchers have reported that the field performance of PVD is far slower than theoretical prediction especially due to the smear column which forms around the vertical drain due to penetration disturbance. Indraratna and Redana (1997, 1998), Bo et al. (1997) and Hansbo (1981) reported that the consolidation rate in the field is much slower than that calculated due to the smear effect. Bo (2004) has reported that excess pore pressure during penetration was detected even at a distance of 1.3 m from the installation point of PVDs (Fig. 3), but was not detected at a distance of 2.85 m. This implies that the disturbance covered an area of radius greater than 1.3 m but not more than 2.85 m from the mandrel. The extent of the smear zone and ratio of permeability reduction are largely dependent upon the type and sensitivity of the clay, size and shape of the mandrel, size and shape of the anchor and equipment used for the installation works.

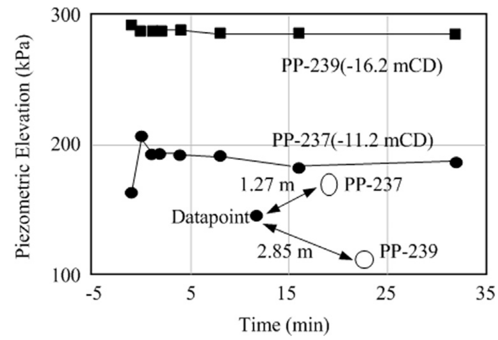


Fig. 3. Pore Pressure Measurements during Mandrel Penetration.

Depending upon the type of clay and anticipated disturbance, a suitable and conservative smear effect parameter should be applied in the design. Since there were several unknown factors in the in-situ condition such as coefficient of consolidation due to horizontal flow (C_h), smear zone ratio and permeability reduction ratio. The permeability reduction ratio is defined as the ratio between reduced permeability due to smearing of soil during mandrel installation and original undisturbed permeability. Several pilot test areas with different PVD designs were constructed in the project site prior to the selection and installation of PVDs to determine the optimum PVD design consideration.

5. Quality control on prefabricated vertical drain material

Generally, PVDs were delivered to the site in rolls of 200–300 m in length. A single delivery to the site could consist of up to one million meter lengths of PVDs delivered in ten containers. Therefore, the specification required full scale testing of PVD materials for every one million meter length of PVD delivered to the site by a third party accredited laboratory. An in-situ specialized laboratory was also set up at the project site to verify the discharge capacity of every 100,000 m length of PVD to be used for installation as well as for carrying out other tests such as Apparent Opening Size (AOS), permeability and specialist tests under various conditions.

In addition, another on-site laboratory was set up by the PVD installation contractor to carry out routine discharge capacity and tensile strength tests on every 20,000 linear meter lengths of vertical drains. Consistency in the quality of PVD was monitored and controlled based on the results from these three laboratories.

6. Control parameters and test results

6.1. Dimensions of PVD

The PVD supplied by various manufacturers had the same dimensions: the standard dimensions were 100 mm width and 4 mm thick, and some larger dimension of PVDs were produced for special purposes. The specifications of the project required the PVD dimensions to be 100 ± 2 mm width and 3 to 4 mm thickness and most PVDs complied with the specified dimensions although some were found to be slightly less than the specified margin. The effect of PVD dimensions on the consolidation time is shown in Fig. 4. It is evident from Fig. 4 that variation of time required for 90% consolidation with specified spacing due to maximum dimension variations of 6 mm in width and 2 mm in thickness in certain types of soil is found to be only 12 days for approximately one year consolidation duration. The maximum percentage difference for one (1) year duration design was only 3%. Since the thickness controls the consolidation time, the thickness and width of the PVD under pressure were frequently checked. At the site laboratory, the width was measured by a vernier scale. Changes in the thickness under pressures were measured at the site laboratory using direct simple shear equipment, which could measure accurately vertical displacements under different loads. Fig. 5 shows variation in the thickness of PVDs under various normal pressures. It is evident in the figure that the variation of thickness of Colbond type PVD was greater than that of the Mebra type PVD; however, both types met the specifications requirements.

6.2. Apparent Opening Size (AOS)

An Apparent Opening Size (AOS) requirement was specified for the PVD filter material. Since the function of the filter is to prevent fine-grained soil from entering into the core and create a clogging potential (Basu and Madhav, 2000) and at the same time to provide sufficient permeability, an AOS of O_{95} (opening size for 95% retained by weight) less than or equal to 75 μm was specified. For a woven or non-woven geotextile, if AOS is smaller than D_{85} (grain diameter for 85% passing by weight) of the surrounding soil, piping will not occur. The D_{85} of natural soft clay at this site was generally greater than 75 μm. Therefore, specifying O_{95} of 75 μm was sufficient to retain the surrounding soil. On the other hand, the AOS of O_{95} or O_{15} (opening size for 15% retained by weight) should also be large enough to prevent clogging. The following criteria were implemented in the project to prevent clogging as recommended by Bo and Choa (2004)

$$\mathrm{AOS} = O_{95} \geq 3D_{15} \quad (1)$$

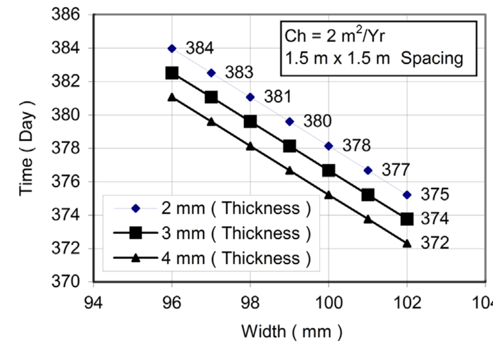


Fig. 4. Time required to complete 90% degree of consolidation with various dimensions of PVDs.

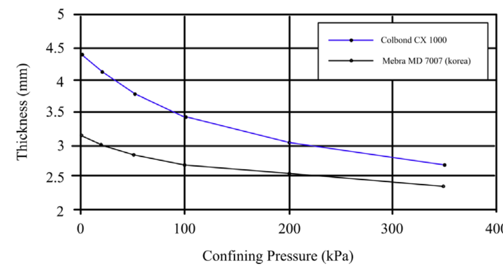


Fig. 5. Variation of thicknesses of PVDs under various normal pressures.

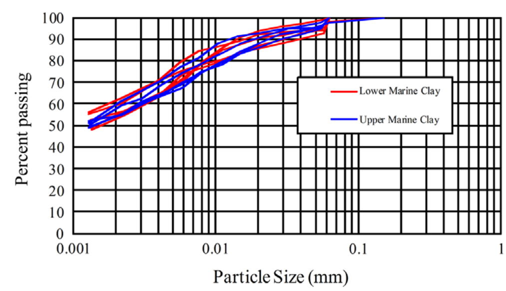


Fig. 6. Grain size distribution of Singapore Marine Clay.

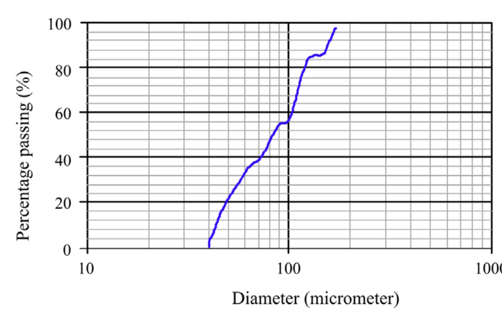


Fig. 7. Cumulative particle size distribution chart for standard glass beads.

or

$$O_{15} = 2\text{–}3D_{15} \quad (2)$$

The typical grain size distribution of Singapore Marine Clay at Changi is shown in Fig. 6. The AOS of O_{95} of 75 μm is much greater than D_{15} of natural clay at Changi. Therefore, the filter would not become clogged in Singapore Marine Clay. The mineralogy and geotechnical properties of Singapore

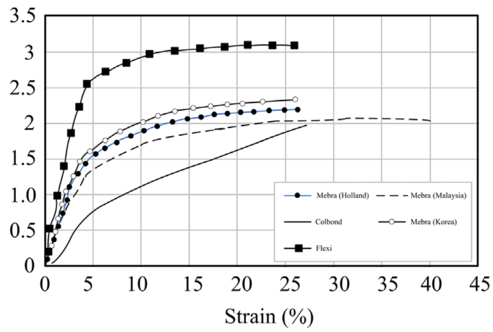


Fig. 8. Tensile strength test results on various PVDs under wet condition.

Table 6
Permeability of various PVDs.

Types of drain under laminar	Permeability flow at 20° (1×10^{-4} m/s)
Colbond CX 1000	15
Mebra (Holland)	1.6
Mebra (Korea)	1.58
Mebra (Malaysia)	1.02
Flexi	4.25

Marine Clay at Changi have been reported recently by Bo et al. (2015).

The AOS tests were carried out using standard glass beads with grain size of diameter, ranging from 40 to 170 μm. The AOS is obtained from the grain size distribution curve provided by a glass beads manufacturer, as shown in Fig. 7. The test method complies with ASTM D4751 (1987).

6.3. Tensile strength

The PVD should be able to withstand the tensile stresses caused by PVD installation works. Elongation of the PVD may also occur during installation. Therefore, the PVD should have the required tensile strength, at an allowable elongation, and be capable of more or less maintaining the dimensions of the drain without major deformation.

For the Changi East Land Reclamation project, the tensile strength of PVDs was specified as 100 N/cm or 1 kN/10 cm at 10% elongation for both the dry and wet conditions. However, the actual elongation test carried out with vertical drain installation rig showed that elongation of Mebra MD 7007 is as low as 1%. It indicates that the stresses occurring due to the friction between the roll of vertical drain during penetration was insignificant. Typical tensile strength test results of Mebra MD 7007, Colbond CX 1000 and Flexi FD 767 under wet conditions are shown in Fig. 8. It is evident from Fig. 8 that the strain in PVD at the specified tensile strength was normally lower than the specified strain of 10% for most PVDs. The tensile strength tests at the site laboratory were carried out with a modified triaxial compression machine where the PVD was gripped across the whole section at the two ends. The size of the jaw face was 140 mm in width and 50 mm in height. Vertical displacement was measured during extension with linear vertical displacement transducer and the stress incurred was measured using an extension proving ring. The tensile strength tests were carried out under a strain rate of 7% strain/min on PVD samples with a gauge length of 200 mm. The method of testing complied with ASTM D459 (1986). The effect of test strain rate on strength of geotextile was found to be insignificant in the tests.

6.4. Permeability

To meet the permeability requirement for the PVDs, Holtz et al. (1991) suggested that the permeability of the geotextile should be at least 10 times more than that of the surrounding soil. For the Changi East Land Reclamation project, the specified permeability of filter is greater than 5×10^{-6} m/s while the permeability of the soil is in an order of 10^{-9} m/s (Bo et al., 1998). Permeability tests were carried out with a simple constant head permeability apparatus. The apparatus used is in accordance with ASTM D4491-85. The device consists of an upper and lower unit, which were fastened together. The sample was positioned between the two units. There are manometers connected to the upper and lower units for water supply and head measurement. Permeability tests were carried out under various head differences. The permeability measured for various PVDs, by Darcy's method, is shown in Table 6.

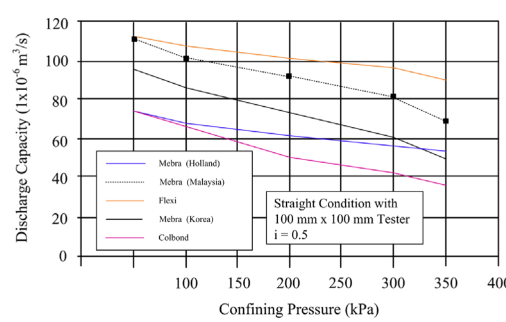


Fig. 9. Discharge capacity of PVDs under straight condition tested with 100 mm × 100 mm tester.

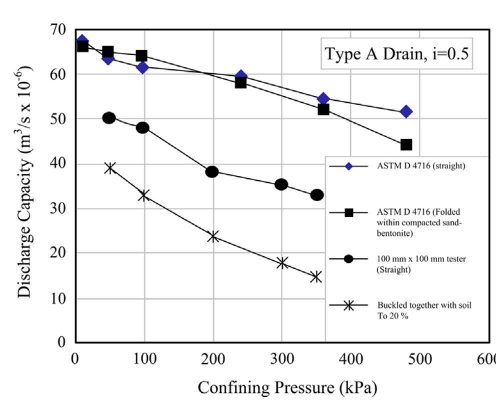


Fig. 10. Variation of discharge capacity of PVDs measured by different types of apparatus.

6.5. Discharge capacity

The discharge capacity of drain is affected by factors such as lateral stress, buckling and siltation. As such, discharge capacity of drains was measured under straight and buckled conditions. The specification requires the discharge capacity to be 25×10^{-6} m^3/s under straight condition and 10×10^{-6} m^3/s under buckled condition with an axial strain of 25% for the Changi East Land Reclamation project. Discharge capacity tests were performed under various lateral stresses and under various hydraulic gradients for straight and buckled conditions. Some of the results of the discharge capacity tests are shown in Figs. 9 and 10.

The discharge capacity under straight condition was carried out with a 100 mm × 100 mm tester, in which the sample was surrounded by soil and tested under various pressures, and various hydraulic gradients. The tester was connected to the inflow and outflow water pipes, which provide the discharge water and measured the outflow discharge rate of water. Manometers were also connected to the tester to measure hydraulic gradient. The discharge capacity test was carried out in a cylinder, under buckled condition, in which the PVD was installed and compressed with surrounding soil. Table 7 shows the discharge capacity of type D PVD under various deformation configurations. It is evident from the results that all the tested types of PVDs met the specified requirement both in straight and buckled conditions. PVDs with corrugated core were found to have comparatively high discharge capacities.

Table 7
Discharge capacity of type D PVD under various configurations of deformation (after Bergado et al., 1996).

Type of deformation	Discharge capacity (m^3/s × 10^{-6})
Non-deform	62
15% free bend	36
20% free band	32
90° twisted	31
180° twisted	30
20% sharp folding	16

7. Field measurements

The field performance of ground improvement work using PVD was monitored and verified by the use of geotechnical instrumentation such as settlement plates, deep settlement gauges installed at various levels and piezometers installed at various elevations within the compressible soil mass both at pilot areas and actual ground improvement areas. Both an acceleration in the settlement and the dissipation of pore pressures were clearly shown in all cases. An example of field performance measurements is shown in Fig. 11. Details of field performance measurements using geotechnical instrumentation were discussed in Bo (2004) and details of assessment of degree of consolidation and performance evaluation were discussed in details in Bo (2004) and Bo (2004).

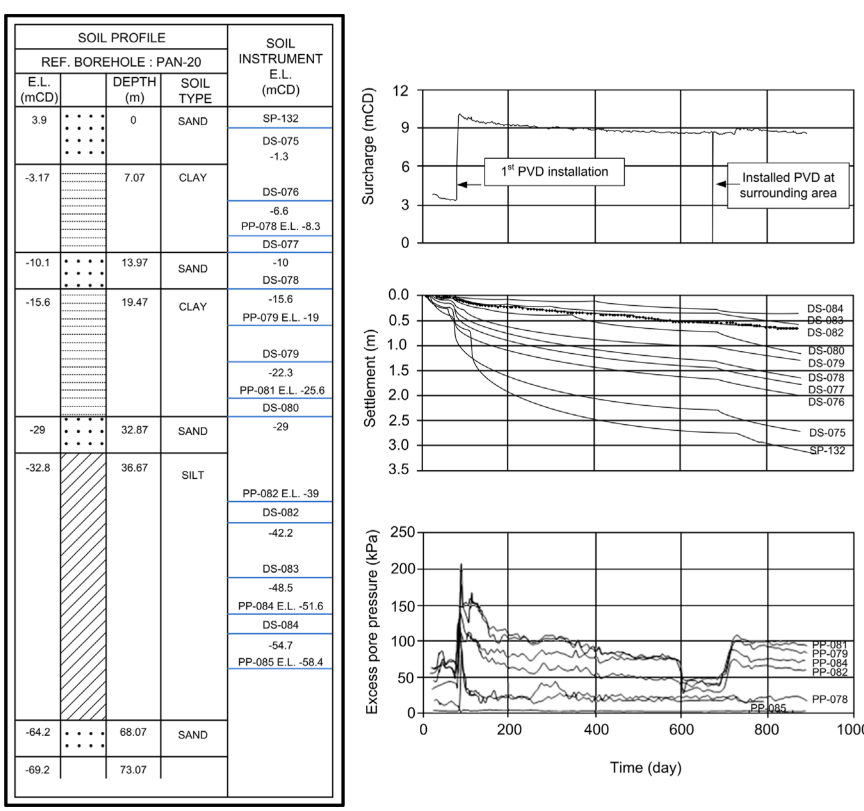


Fig. 11. Settlement and pore pressure measurement at Area A (North) Pilot Area using 1.5 m × 1.5 m drain.

8. Conclusions

This technical report presents the quality management of PVD materials in the mega Changi East land reclamation project in the Republic of Singapore. The following key conclusions are useful and can be applied to other similar mega projects. The quality management of PVD materials involves several detailed processes. Firstly, comprehensive specifications must be adopted for the selection of material. The adopted specification should suit the ground conditions and geotechnical characteristics of the in-situ compressible soils.

Before the commencement of PVD works, the correct planning and deployment of suitable types of PVD installation rigs and accessories such as mandrels and anchors are essential. The selected installation rig should be suitable for the prepared installation platform. The chosen mandrels and anchors should be suited for the in-situ soil during installation.

It may also be necessary to mobilize special type of rigs if difficulties are encountered in the installation, such as hard or dense layers at any depth or very soft soil conditions. The construction of pilot trial embankments with several types of PVD spacing and configurations are required in order to verify the design spacing with the selected material, installation equipment and accessories.

Establishing a quality control system, consisting of on-site laboratory and third party laboratory, is absolutely necessary to control the quality and consistency of the supplied PVD materials. Having an in-situ laboratory specialist on site should also be considered in order to assess the measured parameters and variation of parameters with the various test and equipment conditions. Based on the quality control tests carried out on the PVD materials used against specified parameters shown in Table 1, the supplied PVDs generally met the required specification and performed well in the field.

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